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H. O. Weeren

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SHALE FRACTURING INJECTIONS AT OAK RIDGE NATIONAL LABORATORY — 1977-1979 SERIES

H. O. Weeren

Date Published: September 1980

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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ABSTRACT

Intermediate-level waste solution generated at ORNL is periodically mixed with a cement-base blend of dry solids and injected into an impermeable shale formation at an approximate depth of 240 m (800 ft). The grout mix sets shortly after the injection, permanently fixing the radionuclides in the shale formation. A series of four injections of intermediate-level waste solution was made between 1977 and 1979. A total of 1.2 million ℓ (314,000 gal) of waste solution containing 81,780 Ci of radionuclides was injected. This report is an account of this injection series — preparations, injections, results, and conclusions. The volumes and activities that were injected can be summarized as follows:

Injection	Date	Volume of waste (ℓ)	Volume of waste (gal)	Volume of grout (ℓ)	Volume of grout (gal)	Activity (Ci)
ILW-15	6-30-77	344,400	91,000	549,000	145,037	26,528
ILW-16	11-17-77	208,200	55,000	301,000	79,500	15,982
ILW-17	9-1-78	311,500	82,300	520,400	137,500	22,362
ILW-18	5-19-79	325,600	86,014	526,100	139,000	16,908
		1,189,700	314,314	1,896,500	501,037	81,780

In Injection ILW-15 a small leak of grout to the waste pit eroded the drain valves and forced a shutdown of the injection while repairs were made. The injection was completed 2 days later. Injection ILW-16 was terminated about two-thirds through the injection when the diesel drive of the injection pump blew a connecting rod through the block. The facility and well were washed down with the standby pump. Prior to Injection ILW-17, air pads were installed on all bulk solids storage bins. All subsequent injections have been marked by a much more even flow of solids and a resulting improvement in the mix ratio control. Injections ILW-17 and ILW-18 were made without notable incidents.

Logs of the observation wells indicated that all grout sheets were within the disposal zone.

1. INTRODUCTION

The shale fracturing process has been used for the routine disposal of intermediate-level waste solution at the Oak Ridge National Laboratory (ORNL) since 1966. In this process the waste solution is mixed with cement and other additives; the resulting mixture, or grout, is then injected into an impermeable shale formation at a specific depth between 200 and 300 m (700 and 1000 ft) — well below the level at which groundwater is encountered. The injected grout forms a thin, approximately horizontal sheet several hundred meters (up to 1000 ft) across during the course of the injection. The grout sets shortly after completion of the injection, thereby permanently fixing the radioactive wastes in the shale formation. Subsequent injections form sheets that are approximately parallel to the preceding sheets.

Reports summarizing the 1972 and 1975 series of injections have been published;[1,2] the experimental development program and the first two operational injections are detailed in ref. 3. Following the 1975 injection series, the injection facility was used for four injections of concentrated intermediate-level waste (ILW). This report describes the preparations, operational procedures, and data for these injections individually, and then discusses the results and conclusions from the series as a whole.

2. DESCRIPTION OF PROCESS AND PLANT

In the shale fracturing process an alkaline waste solution is mixed with a solids blend composed of cement and other additives and then injected, under pressure, into a bedded shale formation at a specific depth between 200 and 300 m (700 and 1000 ft). The pressure of the injected grout is sufficiently high to initiate the formation of a crack between adjacent layers of shale. As the injection continues, the grout fills this crack and extends it further to form a thin, approximately horizontal sheet several hundred meters (up to 1000 ft) in extent. Figure 1 shows an isometric view of the shale fracturing facility.

Three types of wells have been used at the shale fracturing facility: an injection well for the injection of waste grout, observation wells for the determination of the orientation of the grout sheet, and rock cover monitoring wells for verification of the continued impermeability of the shale above the grout sheets. A sketch of each well type is given in Fig. 2. All waste injections are made through slots cut in the casing and surrounding cement of the injection well. As the grout sheet spreads out from the injection well, it intersects the cemented casing of one or more observation wells. A gamma-sensitive probe in the observation well will then detect the presence of the grout sheet, thereby establishing the depth of the grout sheet at that point. The rock cover monitoring wells are used to periodically determine the permeability of the shale cover rock at a depth of 180 m (600 ft).

The major process equipment used to inject a batch of waste consists of a waste pump, a jet mixer, a surge tank, and a high-pressure injection pump; a flow diagram is shown in Fig. 3. Preblended solids are stored in bulk storage bins for use as needed. A standby injection pump is always available to clear the injection well in the event that the main injection pump should fail. During an injection, waste solution is pumped to the mixer, continuously mixed with the preblended solids, and discharged into the surge tank. From the surge tank the grout is pumped down a tube hung in the injection well and out into the shale formation.

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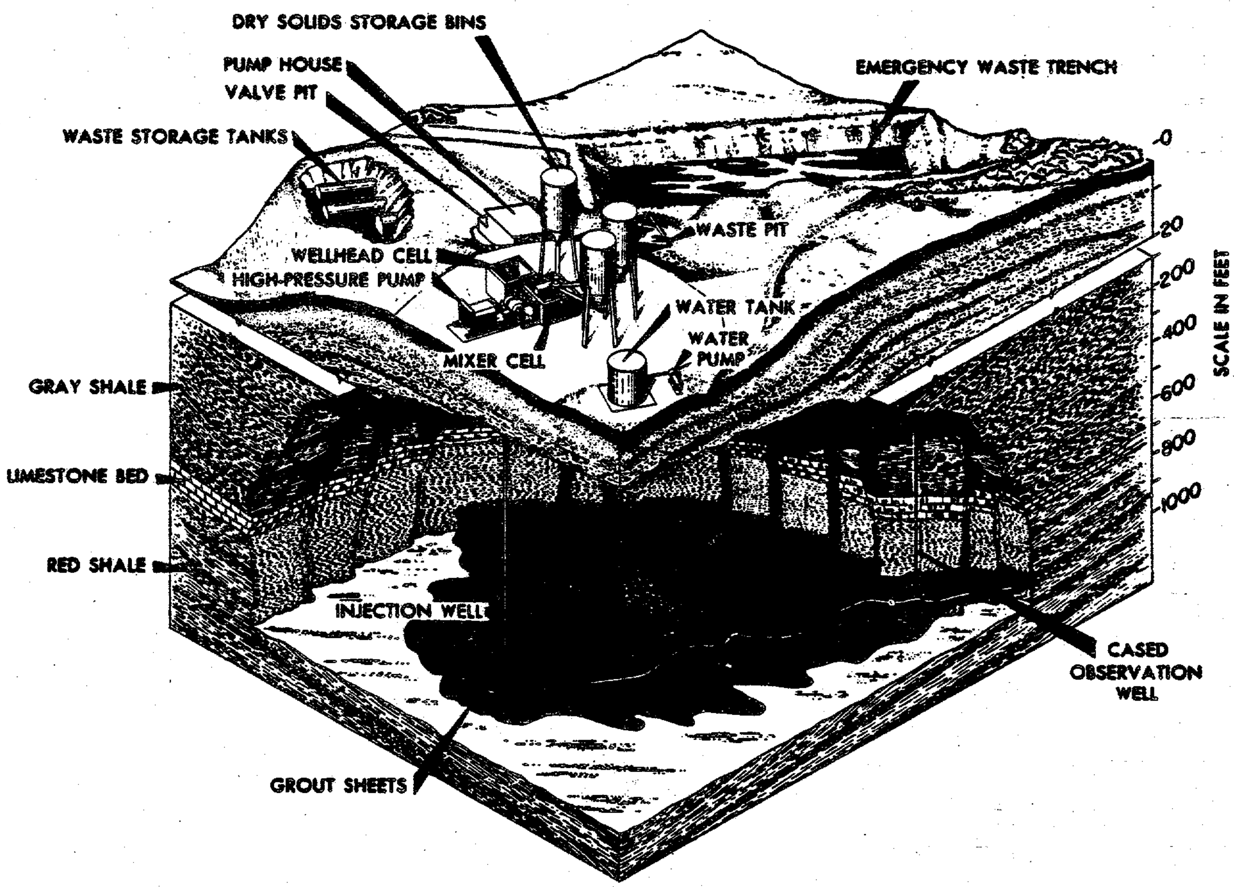

Fig. 1. ORNL Shale Fracturing Disposal Plant.

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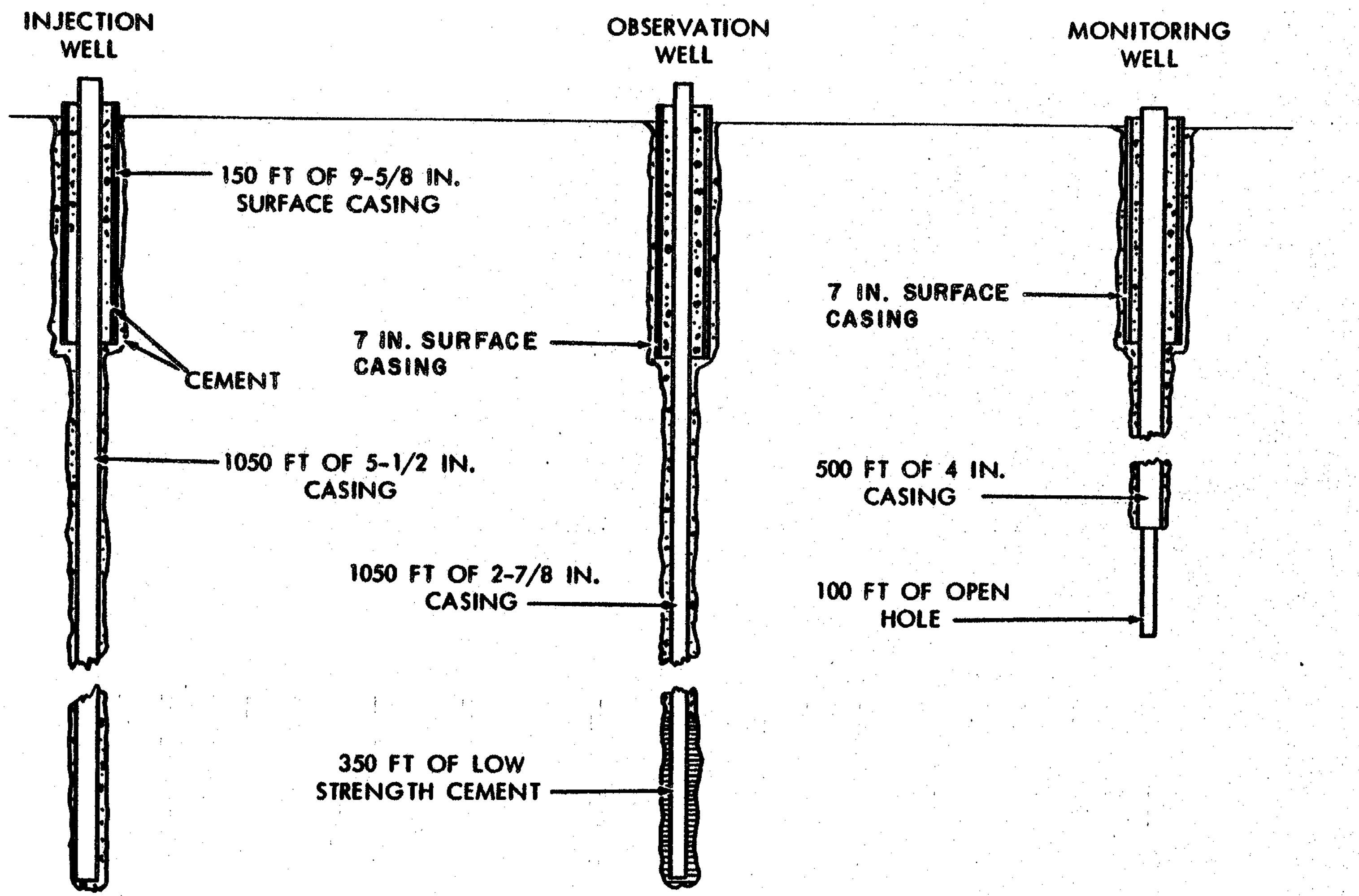

Fig. 2. Sketch of wells for fracturing facility.

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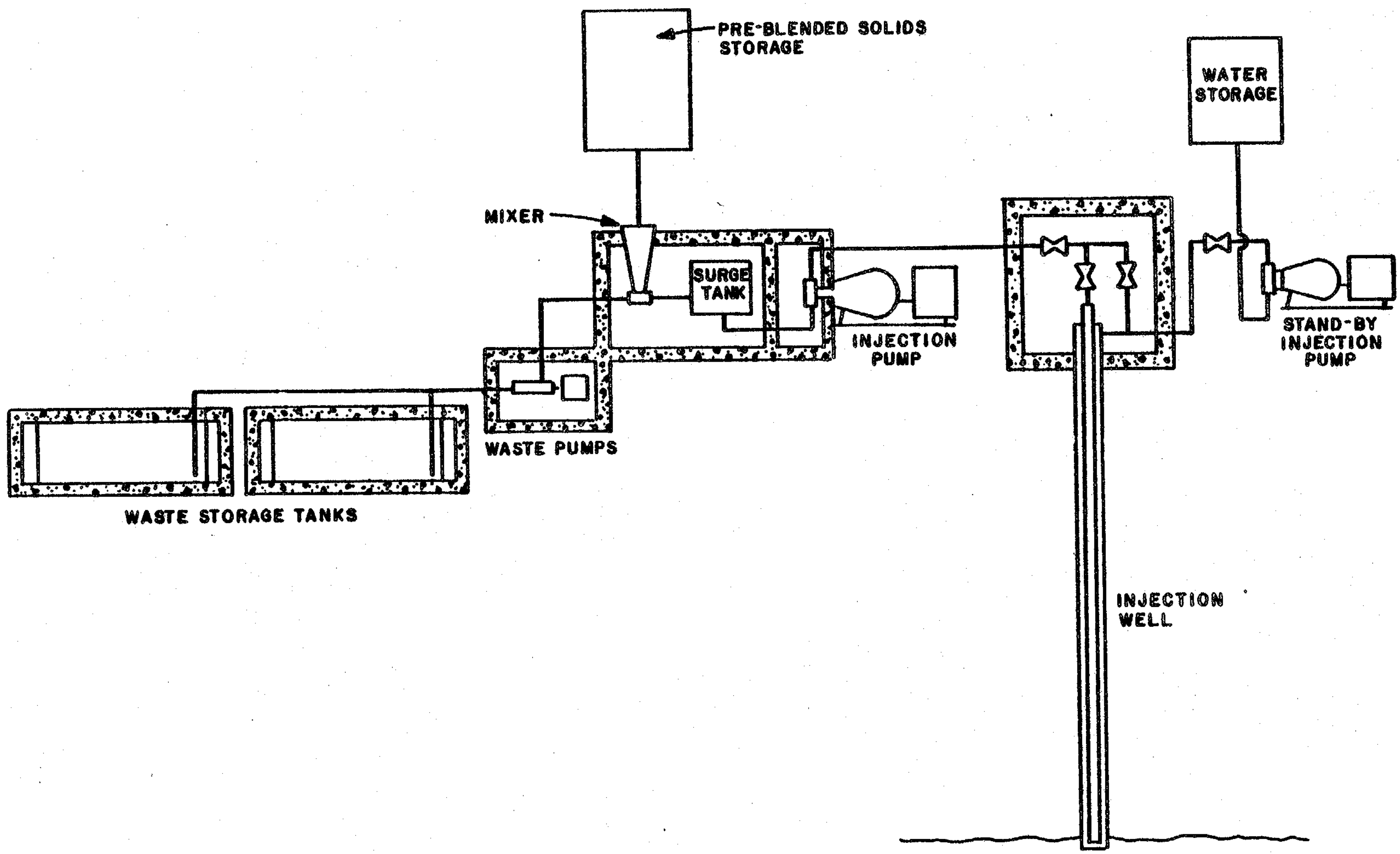

Fig. 3. Flow diagram of shale fracturing facility.

Five underground waste storage tanks, with a total capacity of 340,000 ℓ (90,000 gal), are installed at the shale fracturing plant. Prior to each injection, the waste solution is pumped to the site through a waste transfer line at the rate of ~75 ℓ/min (20 gpm) and stored in these tanks.

A week or more before an injection, the solids — cement, fly ash, Attapulgite 150 (a water-retaining clay), a clay for cesium retention, and a retarder — are brought to the fracturing site, blended in the desired proportions in a weigh tank, mixed by blowing them back and forth between two pressure tanks (P-tanks), and stored in four bulk storage bins. These bins [capacity, 66 m^3 (2780 ft^3) each] are 3.7 m (12 ft) in diameter and installed on legs so that their bottoms are ~1.8 m (6 ft) above the top of the mixing cell. During an injection, the contents of each bin in turn are aerated and flow through an air slide (an enclosed chute that is continuously aerated from below) into a metering hopper in the mixing cell and, from there, into the mixer.

The jet mixer is a device for mixing the waste solution and the solids. As the waste solution is pumped through the mixer, the solids drop into the mixer and are subsequently picked up by the jet stream and thoroughly mixed with the waste. The resulting grout is continuously discharged into the surge tank. The mixer bowl is connected to the hopper to confine the solids and any grout that might splash out of the mixer. For convenience, an observation window is provided.

The surge tank allows the flows of the waste transfer pump and the injection pump to be synchronized during an injection. A single operator, who controls both pumps, observes the level of grout in the surge tank either by means of a mirror-and-window arrangement on the top of the tank or by observing a float-type level gage. He adjusts the flow rate of one or the other of the pumps as the grout level fluctuates. During an injection, air is withdrawn continuously from the surge tank, filtered through a high-efficiency filter, and discharged.

The control of the proportions at which solids and waste solution are mixed in the fracturing plant is critical. If the proportion of solids is too high, the resulting grout will be viscous, difficult to pump, and subject to premature setting. If the proportion of solids is too low, the grout will fail to retain all of the associated liquid and will exhibit "phase separation" on setting. This is undesirable because some small fraction of the radionuclides (<<1%) will remain with the water and thus will not be immobilized. The desirable operating range between these two extremes is fairly narrow; the average variation from the desired proportion should not exceed 10% at most and should be kept within 5% if possible. During a waste injection, this mix ratio is determined from separate measurements of the flow rates of the waste stream and the dry solids stream and a manual or automatic calculation of their ratio. The solids addition rate is measured by a mass flowmeter, a device that continuously weighs the flow of solids, installed immediately below the metering hopper. The flow rate of the waste liquid is measured by a turbine flowmeter. During an injection, the mix ratio can be varied by a manual adjustment of either the solids or the waste flow rate. (Generally, the solids flow rate is adjusted.)

Three cells are provided for the mixing and injecting equipment — one for the mixer and surge tank, one for the head end of the injection pump, and one for the wellhead and associated piping. All cells are made of a 30-cm (12-in.) thickness of concrete block and are roofed with a 1.9-cm (3/4-in.) grating covered with sheet metal. The cells are painted but unlined. The roof of the mixer cell is fixed in place; the roofs of the pump cell and wellhead cell are removable. Because the process piping in the pump cell and the wellhead are under considerable pressure during an injection [up to 34.5 MPa (5000 psi)], the vision ports in these cells are made of bulletproof glass and the roof grating is covered with 0.6-cm (1/4-in.) steel plate on both sides. Access may be gained to the cells through a hatch in the roof of the well cell and a door in the wall of the pump cell.

The injection pump* is capable of operating over a range of pressures and flow rates between 41.4 MPa (6000 psi) and 400 ℓ/min (105 gpm) and 6.9 MPa (1000 psi) and 2650 ℓ/min (700 gpm). A steel splash plate, which is

*A Halliburton HT-400 triplex positive-displacement pump.

fitted around the head of the pump and extends to the walls, floor, and roof of the cell, isolates the pump head within the cell.

A standby injection pump,* similar to the main injection pump, is rented for each waste injection. During an injection it is connected, via the wellhead manifold, to the injection well. Its function is to provide a means for flushing the well free of grout in the event that the main injection pump fails. This pump is not required to transfer radioactive fluids.

A piping manifold connects the injection pump, the injection well, the standby injection pump, and the waste pit. This manifold contains 10 plug valves, 2 check valves, a pressure relief valve [set at 41.4 MPa (6000 psi)], a pressure gage connection, and 13 unions. The components of the manifold are rated at $\geq$69 MPa ($\geq$10,000 psi). Extra high-pressure Chiksan swivel joints are used between the injection pump and the piping manifold, and between the piping manifold and the wellhead, to damp vibration between the pumps and the wellhead.

A considerable volume of water is required for operations such as slotting the casing of the injection well and washing equipment after an injection. Since this water will become contaminated, it must ultimately be injected with the waste solution. Water must be reused, where feasible, to prevent the contaminated water from constituting a large fraction of the waste being injected. The waste pit, a concrete pit 3.6 × 3.6 × 2.7 m (12 × 12 × 9 ft) deep, was built to serve this function. Washup water and water that is used in slotting operations drain to the waste pit and are pumped out of the pit by the waste pump for reuse.

An emergency waste trench is provided as a precaution against the unlikely possibility that, late in the course of a waste injection, the wellhead might rupture and allow the injected grout to flow back up the well. In such an event, the grout would flow from the wellhead cell through an 48-cm (18-in.) line to the 400,000-ℓ (100,000-gal) waste trench where it would set and be covered with earthfill.

A cell off-gas system removes 595 m^3/min (2100 cfm) of air from the mixer cell, pump cell, and wellhead cell, through a roughing and a

*A standard truck-mounted Halliburton positive-displacement pump.

high-efficiency filter in series, and exhausts it through a short stack. A separate off-gas system provided for the surge tank exhausts through a demister mounted above the tank and a high-efficiency filter, and then discharges the air to the suction side of the cell off-gas filters.

Necessary information on the progress of an injection is obtained from readings of the waste tank levels, the waste flow rate, the grout flow rate, the solids flow rate, and the injection pressure. The orientation of the grout sheet is determined by logging the various observation wells after the injection has been completed.

Small volumes of free water can be formed in the disposal zone by phase separation of the injected grout. Even though this phase-separated water contains only a small fraction of the radionuclides that have been injected (<<1%), provisions are made for its removal. After each injection or series of injections, the wellhead shutoff valve is opened and any free water is bled back through the injection well and collected. Ultimately, this recovered water is returned to the waste collection system in Bethel Valley.

Four injections are normally made into a single slot in the injection well. Prior to the next series of four injections, the old slot is plugged with cement and a fresh slot is cut in the injection well casing 3 m (10 ft) above the previous one. The technique for cutting the well casing consists of pumping a slurry of sand and water down a string of tubing hanging in the injection well and out a jet at the bottom of the tubing string to impinge on the casing at that point. The erosive action of the sand cuts the casing and the surrounding cement and shale to a sufficient depth to make subsequent initiation of the desired fracture relatively easy. The spent slurry is brought to the surface through the annulus between the tubing and the casing, the degraded sand is allowed to settle in a waste pit, and the water is recirculated so that the volume of contaminated water produced by the slotting operation can be kept to a minimum. A sketch of this operation is shown in Fig. 4. The tubing string is slowly rotated by a hydraulic power swivel so that a complete cut of the casing is made.

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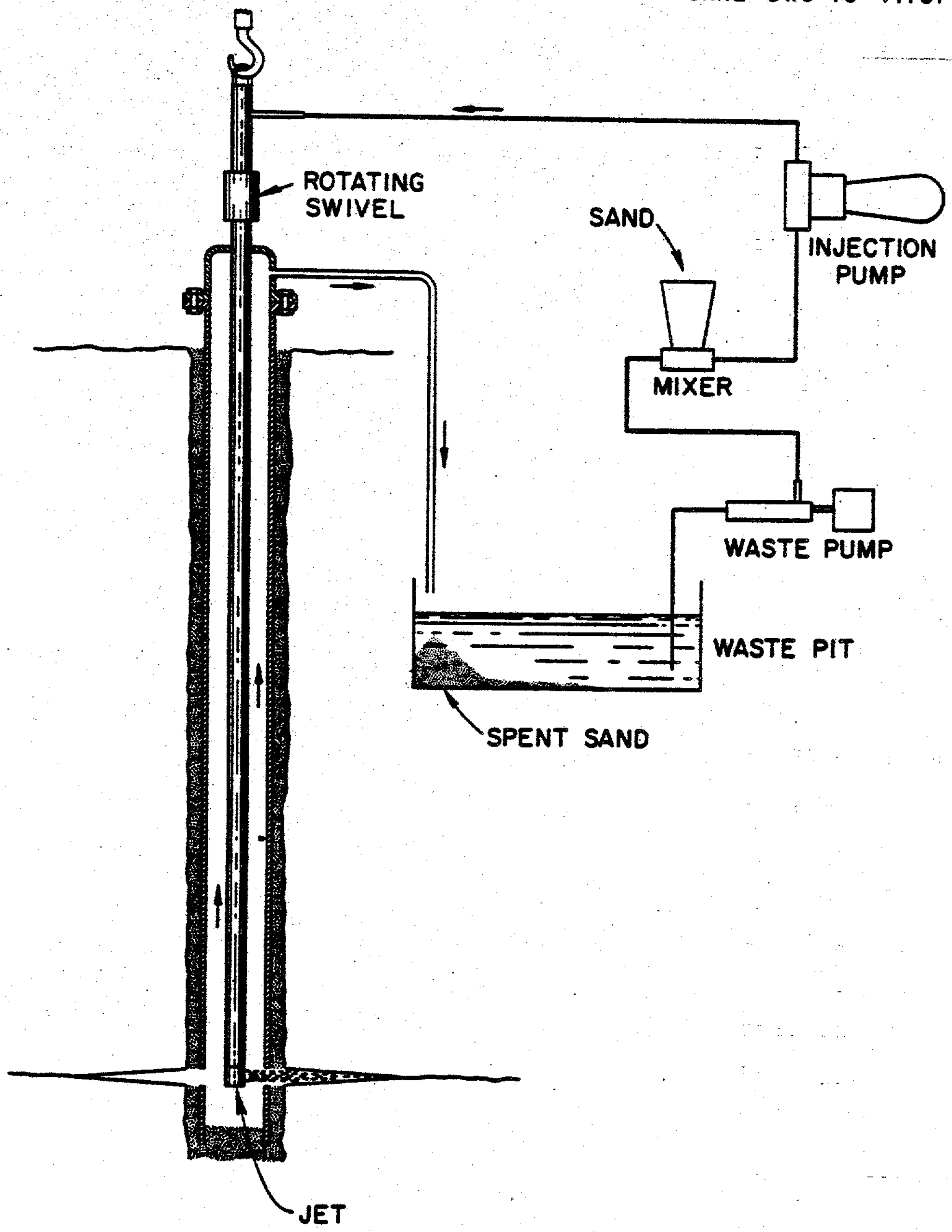

Fig. 4. Flow diagram of slotting operation.

The mix ratio to be used in each injection is determined prior to the injection by a series of "compatibility tests." For these tests, samples are taken of the dry solids that were blended for the injection and stored in the bulk storage bins. These samples are mixed in various proportions with a synthetic waste solution having a composition similar to that of the waste to be injected. The apparent viscosity and the percentage of free water that has separated from the grout after several hours of standing (the phase separation) are determined for each grout sample. The particular ratio of the weight of dry solids to the volume of waste solution that will form a grout with minimum phase separation (preferably <5%) and minimum apparent viscosity (preferably <40 cP) is selected for use during the injection.

3. INJECTION ILW-15

3.1 Preliminary Preparations

3.1.1 Waste transfer and analysis

A proportional sample of the waste solution to be injected is routinely obtained as the solution is pumped from the waste storage tanks in Bethel Valley to those at the shale fracturing site. The sample is analyzed, and the results are used to establish the transuranic content of the waste solution. This analysis ensure that the nonretrievable disposal limit of 10 nCi/g will not be exceeded by the upcoming injection. It is also used to prepare a synthetic waste solution for compatibility tests with the blended dry solids.

In the case of Injection ILW-15, the waste transfer operation had to be delayed until a new waste transfer line could be completed; thus the proportional sample was not available until very shortly before the injection was made. The transuranic content and the compatibility tests were by necessity, therefore, based on analyses of grab samples of the waste solution in two of the waste storage tanks in Bethel Valley. A proportional sample was taken and analyzed, but the results were not available until after the injection had been made. The analyses of both the grab and the proportional samples are given in Table 1. The results are similar for soluble components but quite dissimilar for insoluble components.

Waste solution from Tank W-8 was stored in Tank T-1 at the shale fracture site; the other tanks were filled with solution from Tank W-10. The filled tank volumes were as follows: T-1, 55,910 ℓ (14,772 gal); T-2, 55,910 ℓ (14,772 gal); T-3, 93,100 ℓ (24,597 gal); T-4, 93,100 ℓ (24,597 gal); and T-9, 49,000 ℓ (12,947 gal).

3.1.2 Solids blending

Five batches of dry solids were blended and loaded in the storage bins at the fracturing site. Four of these were loaded in the storage bins; the final batch was left in the blending tanks for later transfer to an empty bin. The weights of the various ingredients that were used for the solids mix are given in Table 2.

Table 1. Composition of waste solution for Injection ILW-15

Component	Grab sample W-8	Grab sample W-10	Proportional sample
NO_3^-, M	0.81	0.67	NA[a]
NH_4^+, M	0.016	0.025	NA
Al^{3+}, M	0.019	0.010	NA
Cr^{3+}, M	3.8×10^{-4}	1.9×10^{-4}	NA
K^+, M	0.261	0.120	NA
Na^+, M	2.243	1.435	NA
CO_3^{2-}, M	0.45	0.33	NA
OH^-, M	0.71	0.37	NA
Cl^-, M	0.172	0.162	NA
SO_4^{2-}, M	0.102	0.113	NA
Specific gravity	1.184	1.123	NA
^{137}Cs, Ci/ℓ (Ci/gal)	NA[a]	7.7×10^{-2} (0.29)	6.1×10^{-2} (0.23)
^{90}Sr, Ci/ℓ (Ci/gal)	NA	1.5×10^{-4} (5.73×10^{-4})	4.0×10^{-4} (1.52×10^{-3})
^{60}Co, Ci/ℓ (Ci/gal)	NA	8.5×10^{-4} (3.22×10^{-3})	8.2×10^{-3} (3.09×10^{-2})
^{106}Ru, Ci/ℓ (Ci/gal)	NA	7.3×10^{-4} (2.76×10^{-3})	1.0×10^{-3} (3.92×10^{-3})
^{238}Pu, Ci/ℓ (Ci/gal)	NA	1.2×10^{-6} (4.52×10^{-6})	4.8×10^{-6} (1.82×10^{-5})
^{239}Pu, Ci/ℓ (Ci/gal)	NA	None	1.9×10^{-6} (7.2×10^{-6})

[a]NA = not analyzed.

Table 2. Dry solids mix for Injection ILW-15

	Bin 1	Bin 2	Bin 3	Bin 4	P-tanks
Blending date	6/17/77	6/20/77	6/16/77	6/15/77	6/21/77
Cement, kg (lb)	21,095 (46,410)	21,330 (46,920)	21,140 (46,510)	21,960 (48,300)	21,080 (46,370)
Fly ash, kg (lb)	21,941 (48,270)	21,800 (47,960)	20,440 (44,970)	17,620 (38,760)	23,240 (51,130)
Attapulgite, kg (lb)	8,769 (19,292)	8,634 (18,995)	8,570 (18,850)	8,950 (19,686)	6,890 (15,150)
Clay, kg (lb)	4,390 (9,660)	4,410 (9,702)	4,380 (9,640)	4,490 (9,873)	4,300 (9,460)
Sugar, kg (lb)	25 (54)	25 (54)	25 (54)	25 (54)	25 (54)
Total, kg (lb)	56,221 (123,686)	56,196 (123,631)	54,565 (120,024)	53,030 (116,673)	55,530 (122,164)

The cement used in this injection was Penn-Dixie, Type I. Because cement from this supplier had not previously been used for shale fracturing operations, a sample was obtained and tested with synthetic waste. The resulting grouts were found to behave similarly to those prepared with cement from other suppliers.

The fly ash was obtained from the Southeast Fly Ash Company. This supplier's loading and weighing facilities were reported to be such that the weight of fly ash delivered in each transporter truck would be more nearly uniform than had been the case for deliveries from the TVA Steam Plant at Kingston, Tennessee. The grouts prepared with a sample of this fly ash were found to behave similarly to those prepared with TVA fly ash.

Attapulgite 150 drilling clay was used in this injection. The clay, supplied by the American Art Clay Company, was the "Indian Red" pottery type. The sugar was delta gluconolactone.

3.1.3 Tests of mix compatibility

Samples of the blended dry solids from each of the storage bins were tested with water and synthetic waste solutions. Phase separation was measured, and rheological properties were determined for grouts made with various mix ratios. In most cases, the grouts were prepared by mixing the dry solids and waste solution in a Waring blender at 5000 rpm (to simulate down-hole conditions); however, a few were made at 2000 rpm (to simulate tub conditions). Not all combinations of wastes and solids were evaluated. Instead, each batch of blended solids was tested with only the particular waste solution with which it would likely be mixed during the injection. The results indicated that virtually all combinations of dry solids with synthetic waste or water were much more fluid than had been observed previously. The phase separations of the grouts were higher, and the "viscosities" were lower. The results also indicated that the phase separation of the grout in the formation would be <1% for a mix ratio of 0.96 kg/ℓ (8 lb/gal) with W-8 waste and <3% for a mix ratio of 0.96 kg/ℓ (8 lb/gal) with W-10 waste. Equivalent phase separations were noted in the mix compatibility tests for ILW-14 at 0.72 kg/ℓ (6 lb/gal).

The observed grout "viscosities" were about 20 cP at 0.96 kg/ℓ (8 lb/gal) and 50 cP at 1.08 kg/ℓ (9 lb/gal). Tests with water indicated a phase separation of 4.3% at 1.08 kg/ℓ (9 lb/gal).

The only sample of blended solids that formed grouts with "reasonable" phase separations [i.e., <1% phase separation at <0.84 kg/ℓ (7 lb/gal)] was the one obtained from the blending tanks. Grouts made from this sample had a "viscosity" of 25 cP and a phase separation of <1% at a mix ratio of 0.84 kg/ℓ (7 lb/gal). These solids had not been subjected to the final transfer into a storage bin, and the improved performance may have been the result of this less severe handling.

3.1.4 Facility modifications

The HT-400 injection pump was extensively reconditioned and modified prior to this injection. A new 5-in. fluid end, a rebuilt Fuller transmission, and a new set of remote controls were installed. The new fluid end replaced a fluid end with 4-1/2 in. pistons; the larger piston size will permit slower operation of the pump for the same volume of fluid pumped and should extend packing life. The new transmission replaced an obsolete transmission for which repair parts were becoming difficult to obtain.

The instrumentation of the solid storage bins was modified. A Monitrol remote sounding unit (Monitrol Manufacturing Co.) was installed on bins 1, 3, and 4. This device consists of a hollow steel float (about 10 in. in diameter) on a cable. When a level measurement is desired, the float is lowered until it contacts the surface of the solids and the distance between the top of the bin and the solids level is indicated. On bin 2, the Metritapes were removed and a sonic level indicator (Sonargage, Stevens International, Inc.) was installed to measure the distance between the top of the bin and the solids level by determining the time required for a sound pulse to travel this distance.

During an injection, the mix ratio (the weight of dry solids per volume of waste solution) is determined from mass flowmeter readings of the rate of solids flow and from volume ratio measurements (the volume of grout pumped divided by the volume of waste solution pumped). These two determinations sometimes give conflicting values, and an independent third measurement of this ratio would be useful in such cases. Since the solids that are mixed with the waste solution will both dilute the radionuclide concentration and provide an appreciable amount of shielding, the radiation emitted by a unit volume of grout would be appreciably less than that emitted by an equal volume of waste solution and the decreases should be proportional to the concentration of solids. Two radiation monitors were mounted on the waste line between the waste pump and the mixer cell and on the high-pressure line between the injection pump and the valve rack. Readouts from these monitors were provided in the control room.

New hoses were installed between the mixing tub and the injection pump suction manifold. Also, a new lighting system was installed on the mixing tub. This system consisted of a pair of 12-V spotlights located ∿0.6 m (∿2 ft) above the top of the mixing tub at the end of a tube that was integral with the top of the tub.

3.1.5 Preliminary maintenance

During the 3 days prior to the injection, the valves in the high-pressure system were serviced and the 3-in. master valve was overhauled. The mass flowmeter was cleaned and checked. The Gadco pulse dampeners were replaced with air chambers. A series of adjustments was made to the injection pump transmission, and the injection pump was packed. Finally, the pressure relief valve was cleaned and set, and the well was pressurized to verify that the fracture was open. The fracture accepted water at a rate of 320 ℓ/min (84 gpm) and a pressure of 22 MPa (3200 psi).

3.2 Injection on June 30, 1977

Sufficient solids were on hand to permit the injection of 333,000 ℓ (88,000 gal) of waste [leaving a heel of 3000 ℓ (800 gal) in each tank] and 19,000 ℓ (5000 gal) of water if a mix ratio that averaged no higher than 0.78 kg/ℓ (6.5 lb/gal) were used. Tests of the blended solids had indicated that considerable phase separation would be expected to occur at this mix ratio. The relevance of the phase separation tests to the underground situation (in which the grout sheet sets up under considerable pressure) is not entirely clear, however, and a deliberately light mix ratio of 0.78 kg/ℓ (6.5 lb/gal) was chosen for this injection in an attempt to determine the validity of the test.

The injection was begun at 0904 on June 30, 1977. Wastewater was pumped from the pit to reopen the fracture. Solids flow, which was started from bin 1, disclosed the existence of a hole in one of the air slides that permitted the escape of dry solids from the slide to the mixing cell roof. The injection was halted at 0907 to repair this hole.

The injection was resumed at 0945 with pit water and solids from bin 1. At 0946 the flow was switched from pit water to waste solution (T-4). Some difficulty was experienced with the injection pump transmission; the pump could not be shifted into fourth gear, the most efficient gear for the existing injection pressure, and had to be run at ∿720 ℓ/min (190 gpm), which was ∿75% of the rate in previous injections. The orifice in the jet mixer was too large for this lower flow rate, and the injection was halted at 1002 in order to switch to a smaller orifice. The injection was resumed at 1030.

At 1115 the float on the level measuring device on bin 1 broke from its cable and dropped into the bin. Readings taken up to that time showed considerable point-to-point variation.

During this injection, the mix ratio (weight of dry solids per unit volume of waste solution) was determined by two methods. In the first, the weight of solids consumed during a given interval (as measured by the mass meter) was divided by the volume of waste pumped during the same interval (as measured by the turbine flowmeter). In the second, the volume of slurry pumped by the injection pump during a given interval was divided by the volume of waste pumped during the same interval and this ratio was related to the mix ratio by a previously determined calibration curve. Experience in previous injections has shown that the first method gives more uniform results except when the mass meter is biased by a solids accumulation on the sensing cone. The second method, although less precise and more subject to point-to-point fluctuations, is not influenced by mass-meter bias and thus serves as a useful check on the mass-meter readings.

The mix ratios indicated by mass-meter readings and obtained from pumped volume ratios are plotted in Fig. 5. The discrepancy is large and, except for one interval shortly after noon, consistent. The mass-meter bias, which was recognized quite early in the injection, was estimated to be approximately 140 kg/min (300 lb/min) or 0.24 kg/ℓ (2 lb/gal) [at 510 ℓ/min (150 gpm)]. The injection was subsequently run at an indicated mass-meter mix ratio of about 0.96 kg/ℓ (8 lb/gal) to compensate for this bias.

At 1200, the flow of solids from bin 1 become uneven. The fear that the lost float from the level measuring device might be plugging the bin outlet led us to switch the solids flow to bin 2 at 1212.

A buildup of solids in the mixing cone hopper, which obscured the window, made it necessary to stop the injection at 1305. After the hopper had been washed, the injection was resumed (at 1325). Overheating of the Moyno waste pumps caused another interruption in the injection at 1356. Operation was resumed at 1405. The injection was suspended at 1412 to wash the mixing cone hopper again. Most of these interruptions were caused more or less directly by the difficulties with the injection pump transmission. These difficulties made it impossible to operate the injection pump except at a relatively low flow rate. At this low rate, the flow of solids in the mixer hopper was irregular and tended to stop altogether at times. In an effort to keep the solids flowing, the operators stopped and restarted the Moyno waste pumps more frequently than usual; this mode of operation resulted in the overheating of the pump motors and an occasional tripping of the thermal overload switch.

At 1445, the injection was halted because the waste pits were observed to be almost full of waste grout. It was found that one or more of the valves on the valve rack between the high-pressure system and the drain to the waste pit had eroded and would no longer hold pressure. The master valves on the wellhead were closed; the well cell was entered, and the discharge line from the injection pump was connected directly to the wellhead (bypassing the valve rack). The contents of the waste pit, followed by 5700 ℓ (1500 gal) of water, were then pumped down the tubing string and the tubing master valve was closed. The well cell was entered again, and the discharge line from the injection pump was

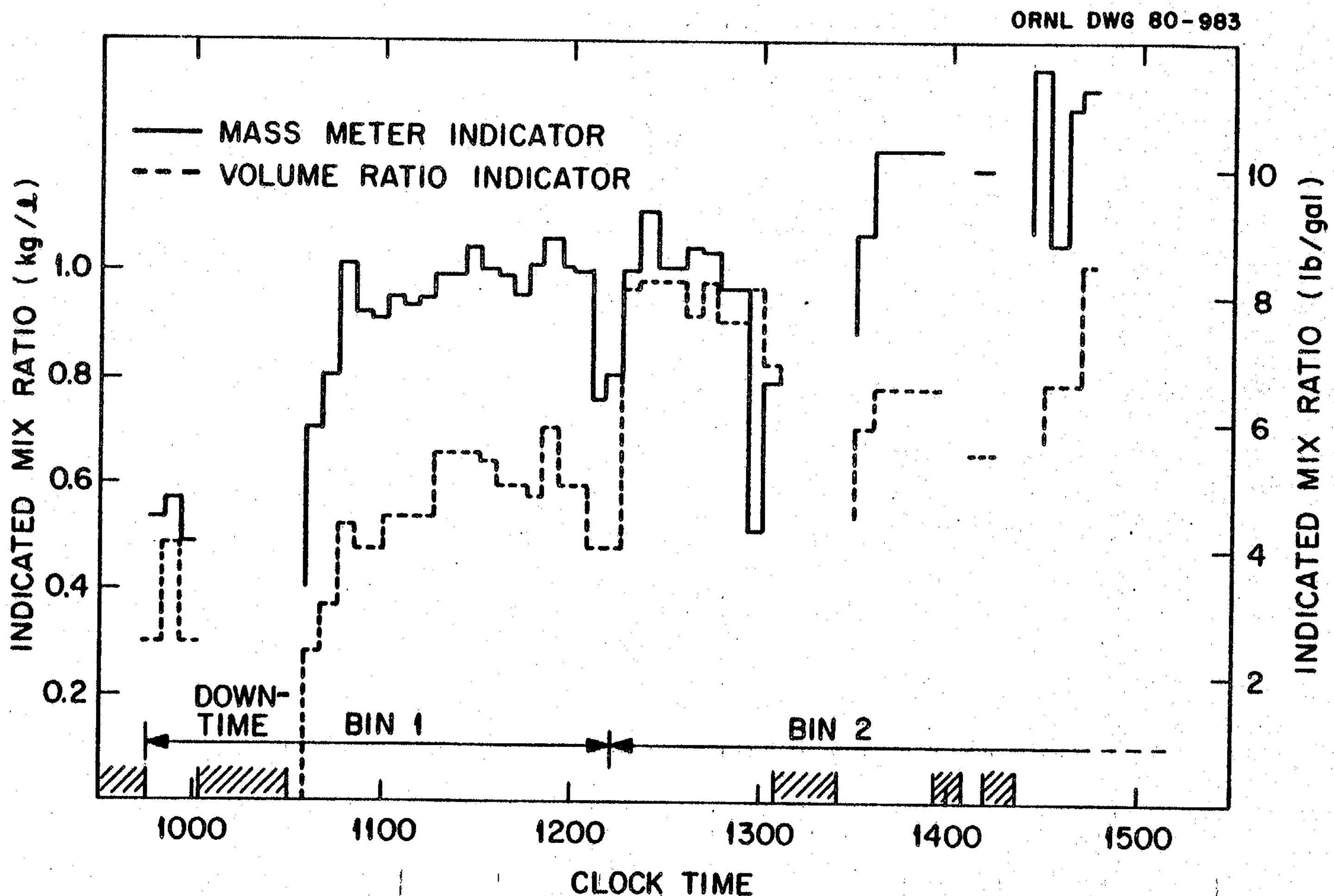

Fig. 5. Indicated mix ratios for Injection ILW-15, June 30, 1977.

connected directly to the master valve on the annulus. After fresh water [5700 ℓ (1500 gal)] had been pumped down the annulus, the annulus valve was closed and the equipment washed.

The waste solution flow rate and the wellhead pressure during this part of the injection are shown in Figs. 6 and 7.

3.3 Interim procedures

On July 1, all high-pressure valves were checked. Three valves (V-2, V-5, and V-8) were found to be too eroded to hold pressure; the valve body was cut on V-8, and this entire valve had to be replaced. The plugs of V-2, V-5, V-3, and V-9 were replaced. The transmission on the injection pump was checked, and the air supply system was modified so that higher-pressure air would be available. On pressurizing the well, the tubing string, the annulus, and the fracture were found to be open. The mass meter was cleaned.

The pressures in the rock cover wells were read both prior to and at intervals during the injection. These readings are given in Table 3. An appreciable pressure rise was noted in two wells, NE-125 and NE-200.

3.4 Injection on July 2, 1977

The injection was resumed at 0815 with water from the waste pit and solids from bin 2. Flow was switched to T-3 after 2 min of operation. Fewer transmission problems were experienced with the injection pump during this part of the injection, and the injection rate averaged between 870 and 910 ℓ/min (230 and 240 gpm).

At 0905, the waste flow was switched to T-4 and the solids flow was switched to bin 3. Bin 2 had contained 56,200 kg (123,600 lb) of solids; the consumption shown by the mass meter was 92,000 kg (202,000 lb). The mass meter was obviously reading quite high, but most of this error probably occurred on June 30 when the mix ratio indicated by the mass meter was as much as 0.48 kg/ℓ (4 lb/gal) higher than the mix ratio calculated from the ratio of the pumped volumes. On July 2, the two methods of measurement were indicating approximately the same mix ratio.

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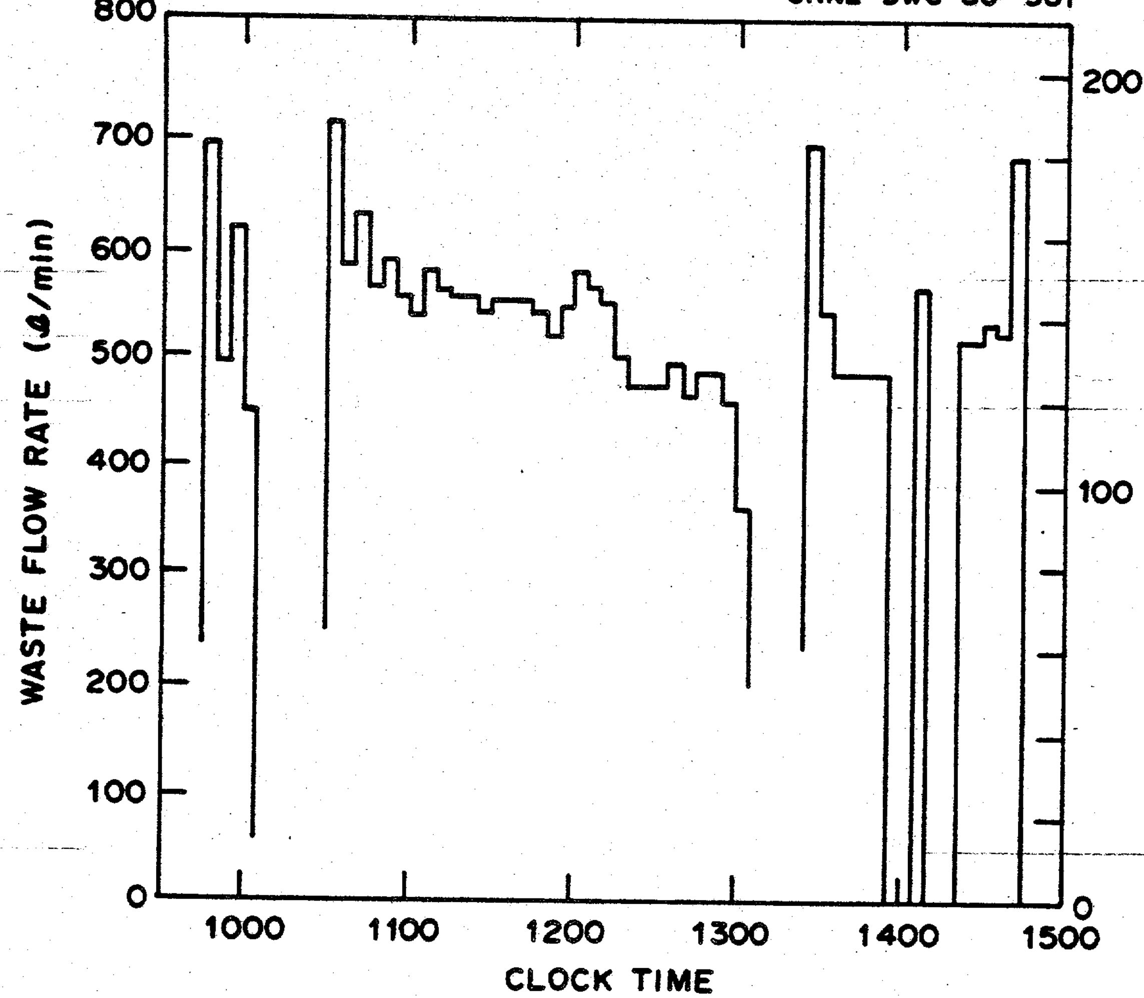

Fig. 6. Waste solution flow rates for Injection ILW-15, June 30, 1977.

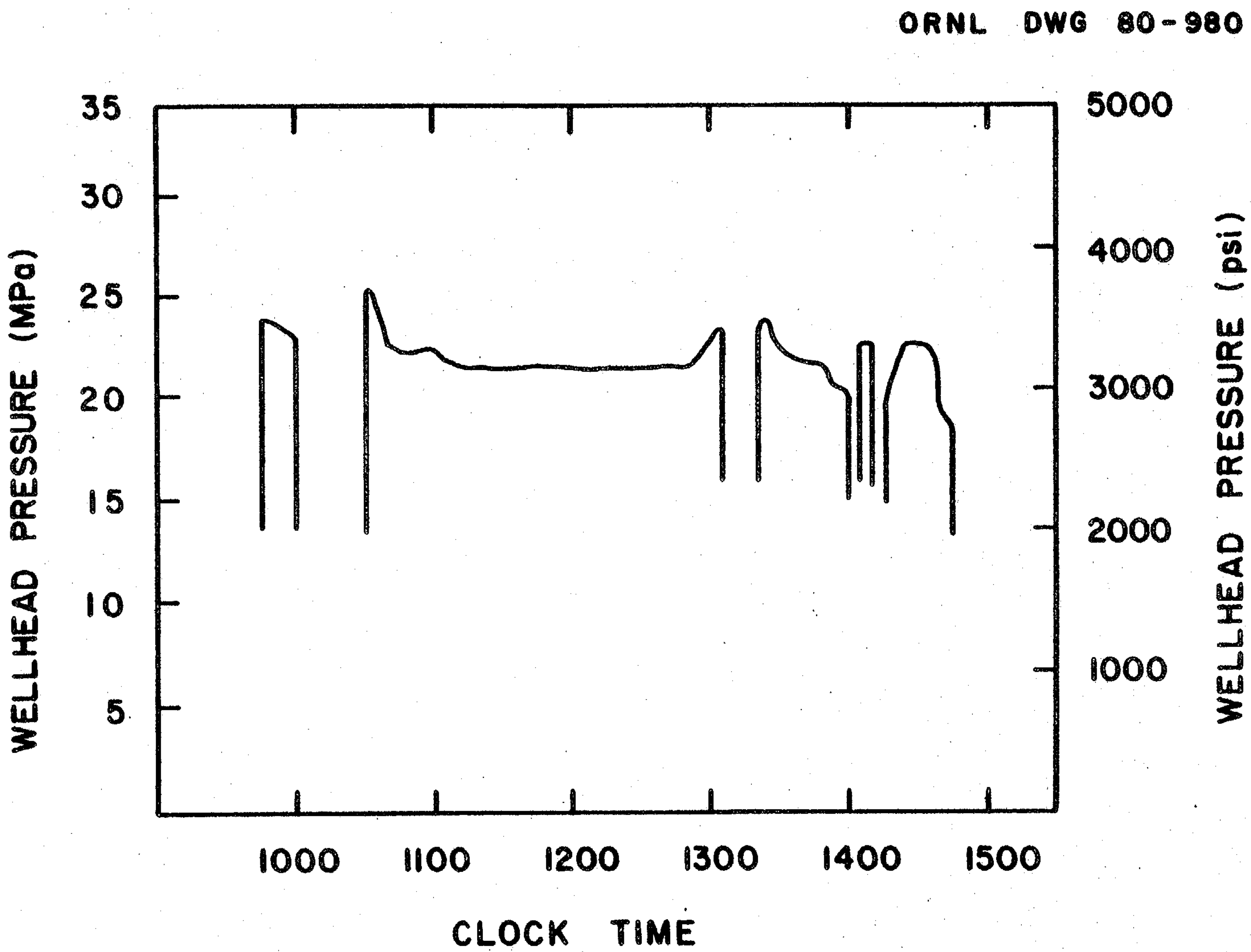

Fig. 7. Wellhead pressure measurements during Injection ILW-15, June 30, 1977.

Table 3. Pressure readings, in kPa (psig), for rock cover wells during Injection ILW-15

Rock cover well	Pre-Injection	Reading taken on June 30, 1977, at: 1030	1200	1340	1505
E-300	76 (11)	83 (12)	72 (10.5)	52 (7.5)	41 (6)
S-200	48 (7)	55 (8)	62 (9)	62 (9)	62 (9)
W-300	-7 (-1)	-7 (-1)	-7 (-1)	-7 (-1)	-7 (-1)
NW-250	14 (2)	14 (2)	0	-14 (-2)	-14 (-2)
NW-175	-51 (-7.4)	-51 (-7.4)	-58 (-8.4)	-68 (-9.8)	-58 (-8.4)
N-275	21 (3)	21 (3)	28 (4)	21 (3)	14 (2)
N-200	-54 (-7.9)	-54 (-7.9)	-58 (-7.9)	-54 (-7.9)	-54 (-7.9)
NE-125	-51 (-7.4)	-51 (-7.4)	69 (10)	86 (12.5)	97 (14)
NE-200	-83 (-12)	83 (12)	172 (25)	221 (32)	203 (29.5)

This is shown in Figs. 8 and 9. Figure 8 shows the calculated mix ratios, and Fig. 9 shows the ratio of these ratios (a means of plotting these values that more clearly emphasizes the difference between them).

At 0924, the injection had to be stopped because the transmission on the injection pump overheated. Inspection revealed that the cooling system for the transmission fluid was inoperative; after this system had been repaired, the injection was resumed (at 0957). During the shutdown period, the mass meter was observed to be indicating a solids flow of 340 kg/min (750 lb/min) with no solids flow. Under the usual operating conditions, this would represent an error in the mix ratio of 0.56 kg/ℓ (4.7 lb/gal). An aberration of this magnitude was probably temporary, but its existence suggested that the mass-meter readings were probably unreliable at this time. Shortly after the injection was resumed, the mix ratio that the operators were attempting to hold was increased to 0.96 kg/ℓ (8 lb/gal) to partially compensate for the mass-meter bias.

At 1142, the flow had to be switched to bin 4 because bin 3 ran empty. Bin 3 had contained 55,000 kg (120,000 lb) of solids; the indicated consumption on the mass meter was 68,000 kg (150,000 lb).

At 1254, the mixer hopper was flooded with cement and the injection was halted to clear the hopper. The injection was resumed at 1321.

At 1433, bin 4 ran empty and the flow was switched to bin 2 (which had been refilled with the solids from the blending tanks). Bin 4 had contained 53,000 kg (116,700 lb) of solids; the indicated consumption on the mass meter was 82,000 kg (180,000 lb) — a 54% error.

At 1510, the Moyno waste pump stopped pumping — the thermal overload switch had kicked out. Although the pump was restarted after a brief pause, it stopped pumping again at 1522. Operation was resumed at 1528, at which time flow was switched to pit water.

The injection was halted to clear the mixer hopper at 1540 but was resumed at 1549. At 1555, the flow was switched to fresh water. At 1618, the injection was terminated. The tubing and the annulus were washed with 800 ℓ (210 gal) and 2400 ℓ (630 gal) of water respectively. The tubing manifold was also washed.

The waste solution flow rate and the wellhead pressure during this part of the injection are shown in Figs. 10 and 11.

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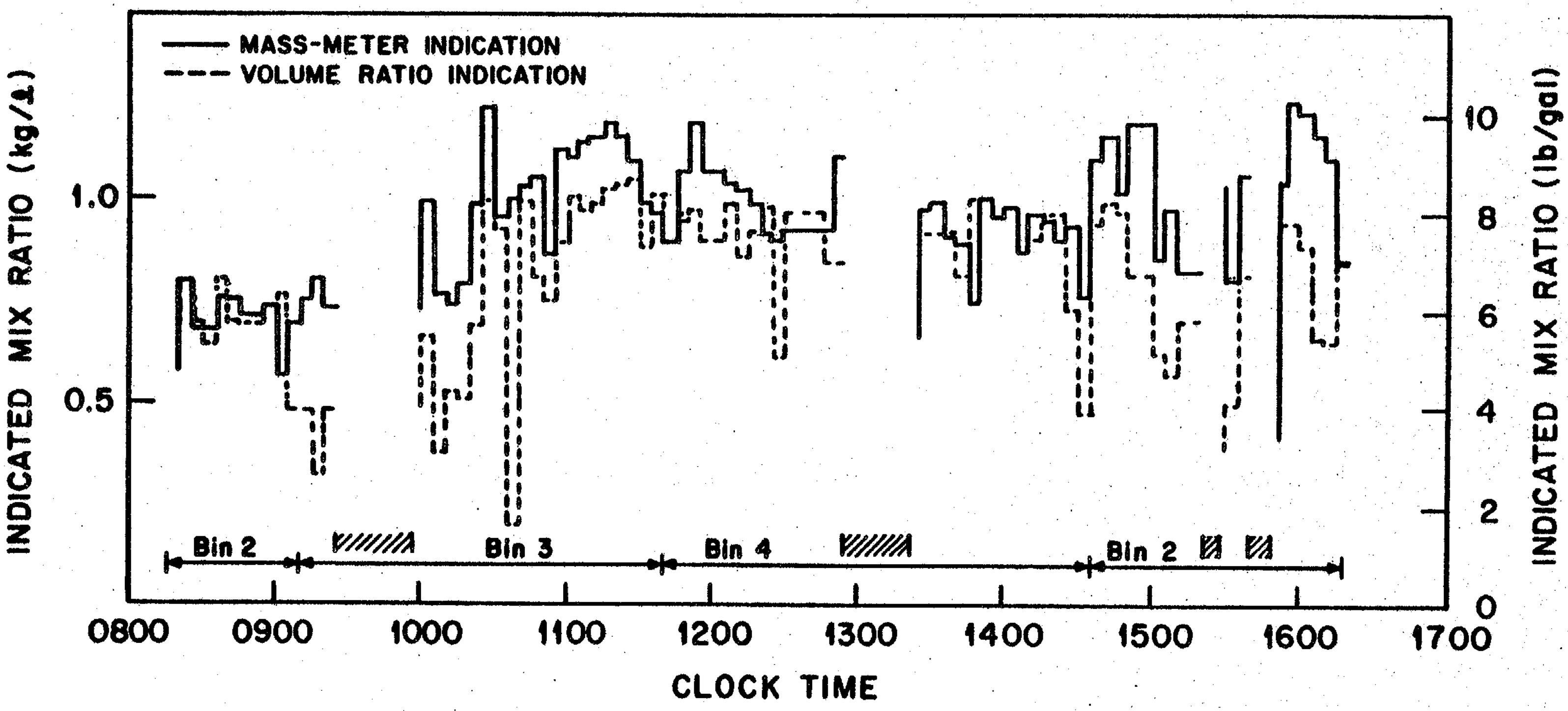

Fig. 8. Indicated mix ratios for Injection ILW-15, July 2, 1977.

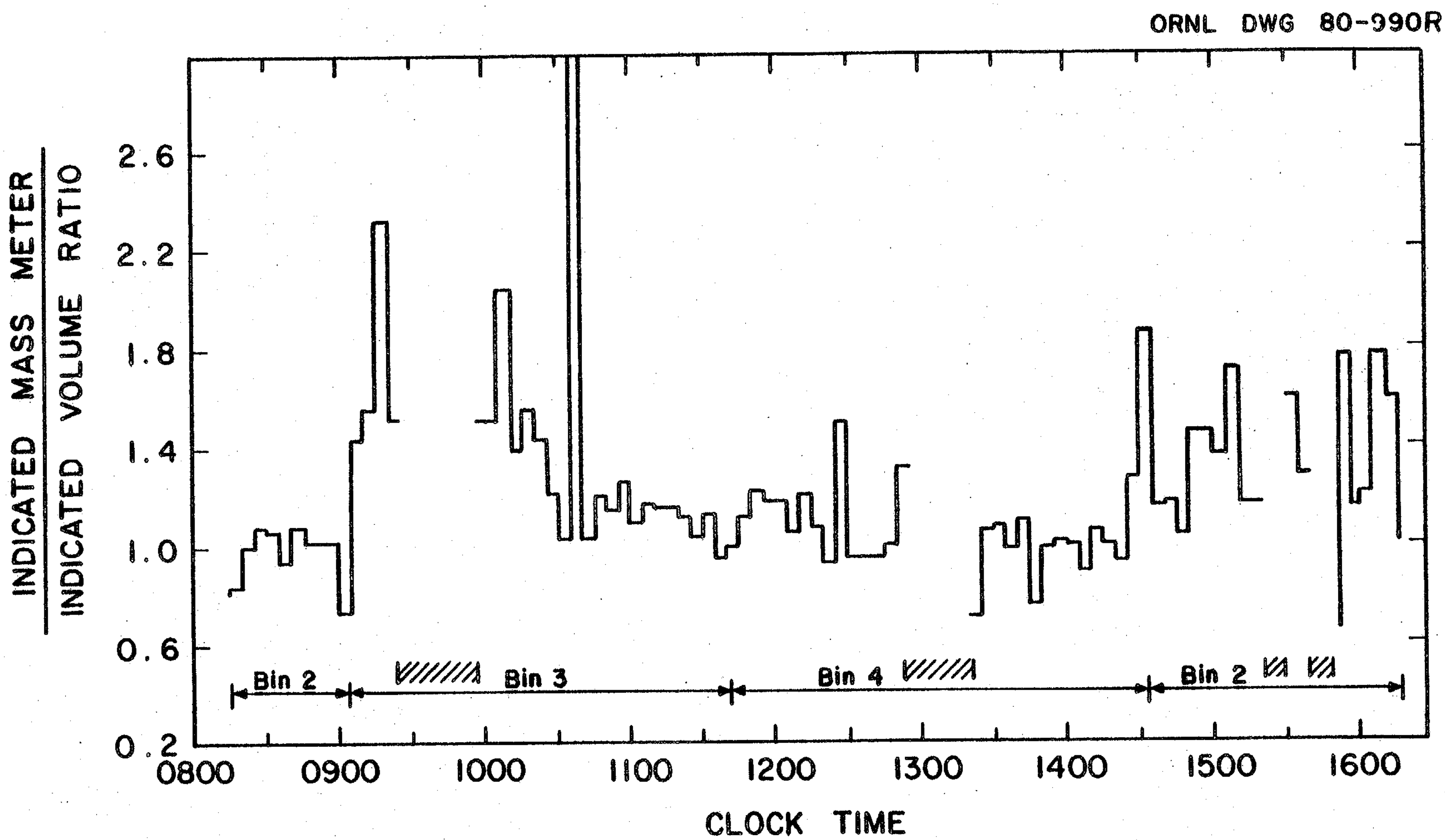

Fig. 9. Comparison of indicated mix ratios for Injection ILW-15, July 2, 1977.

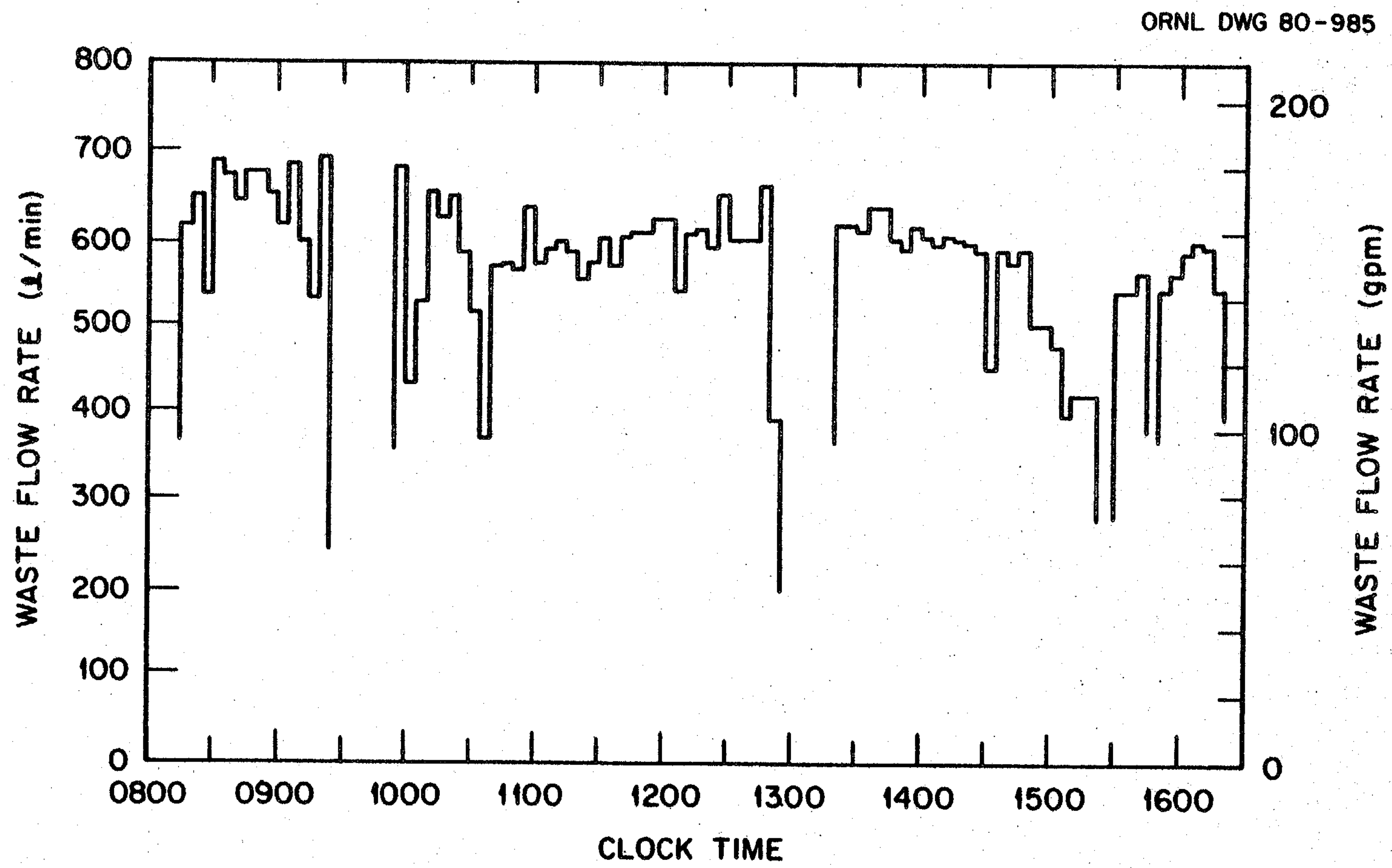

Fig. 10. Waste solution flow rates for Injection ILW-15, July 2, 1977.

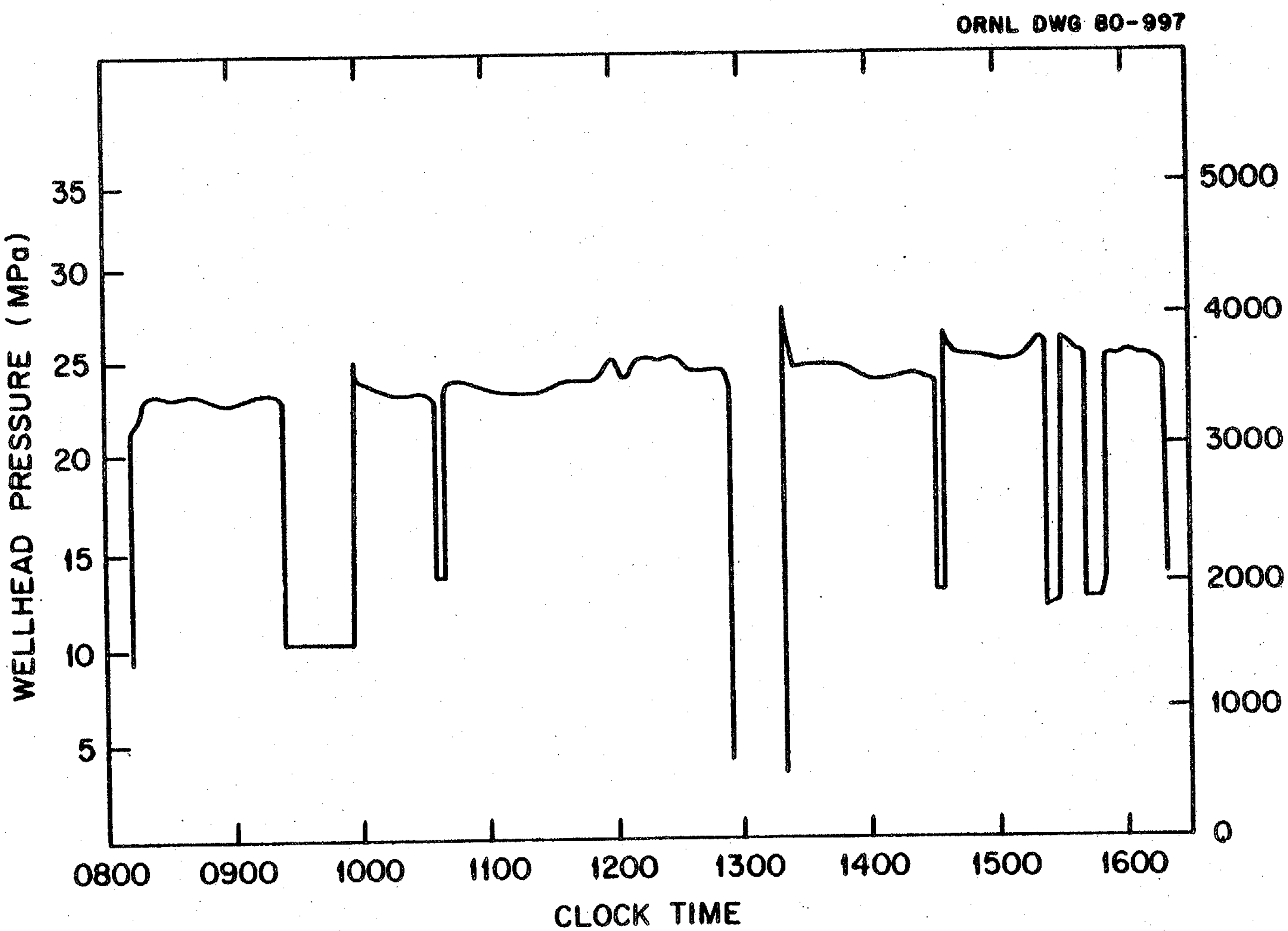

Fig. 11. Wellhead pressure measurements during Injection ILW-15, July 2, 1977.

The waste solution remaining in the waste tanks at the end of the injection totaled 30,500 ℓ (8080 gal) — 2950 ℓ (780 gal) in T-1, 4200 ℓ (1100 gal) in T-2, 13,800 ℓ (3650 gal) in T-3, 6600 ℓ (1750 gal) in T-4, and 3400 ℓ (900 gal) in T-9. A considerable amount of solids remained in bins 1 and 2.

Table 4 gives pressure readings for the rock cover wells just prior to the injection and at intervals during the injection. An appreciable pressure rise was noted in five wells: NE-125, NE-200, N-200, NW-175, and NW-250.

3.5 Data Analysis

The volume of waste solution or pit water pumped during this injection was determined by three methods. The solution flow to the mixer was measured by both a Halliburton turbine flowmeter and a recording orifice meter. The waste solution was measured by the change in tank solution level. A comparison of the volumes obtained with the three methods is given in Table 5. During this injection, the orifice meter readings were, for the most part, quite erratic; even when the recorded flow was stable enough to estimate the pumped volume, the agreement of the orifice meter with the tank levels and the turbine meter was generally poor. Agreement of the tank level readings and the turbine meter readings was usually good (within 5%) except for the period after 1350 on July 2 when tank T-9 was being pumped; during this time, the turbine meter was reading ∿15% lower than the tank level measurements indicated. Because the turbine meter readings are typically more convenient to use than the tank level readings, they are used in the subsequent calculations.

The stroke counter on the injection pump was used to measure the volumes of grout that were injected. These volumes were recorded at 5-min intervals throughout both injection days.

The consumption of dry solids was measured by the Halliburton mass flowmeter. The flowmeter readings, which were also noted at 5-min intervals during the injection, were recorded. The known weight of solids charged to each of the storage bins was used as a periodic check on the accuracy of the mass flowmeter during the injection. If the readings of

Table 4. Pressure readings, in kPa (psig), for rock cover wells — Injection ILW-15

Rock cover well	Pre-Injection	Reading taken on July 2, 1977, at: 0925	1230	1450
E-200	69 (10)	66 (9.5)	24 (3.5)	0
S-200	103 (15)	97 (14)	83 (12)	124 (18)
W-300	0	0	0	0
NW-250	7 (1)	7 (1)	69 (10)	103 (15)
NW-175	-37 (-5.4)	-17 (-2.5)	131 (19)	131 (19)
N-275	-7 (-1)	-3 (-0.5)	0	0
N-200	-51 (-7.4)	-54 (-7.9)	-7 (-1)	0
NE-125	103 (15)	176 (25.5)	345 (50)	359 (52)
NE-200	69 (10)	76 (11)	152 (22)	183 (26.5)

Table 5. Comparison of volume measurements from Injection ILW-15

Time	Tank solution	Pumping time (min)	Turbine meter (ℓ)	Turbine meter (gal)	Tank level (ℓ)	Tank level (gal)	Orifice meter (ℓ)	Orifice meter (gal)
June 30								
1040-1125	T-4	45	25,560	6,752	24,100	6,366	22,570	5,962
1216-1300	T-3	44	20,860	5,512	20,610	5,446		
1425-1441	T-3	16	8,360	2,208	8,320	2,199		
July 2								
0825-0855	T-3	30	19,450	5,139	18,750	4,953	19,970	5,276
0910-0925	T-4	15	8,920	2,356	9,470	2,501		
1045-1145	T-2	60	34,940	9,232	35,070	9,265	28,190	7,447
1210-1250	T-1	40	24,850	6,564	25,030	6,613	18,823	4,973
1335-1345	T-1	10	6,050	1,597	6,000	1,585		
1350-1440	T-9	50	28,920	7,642	33,770	8,922	25,960	6,858

the various level devices on the bulk storage bins had been consistent and reliable, they could also have been used to determine the rate of solids consumption. However, these readings were generally too inconsistent and erratic to be used for this purpose. Both the zero and the span of all three strain gage readings were seriously in error. The sonar gage on bin 2 was consistently erratic; thus the readings of this instrument were not recorded. The Monitrol readings showed considerable point-to-point scatter (Fig. 12 is a typical set of readings). Such readings suggest that (1) the solids level in a bin being emptied fluctuates rapidly as ratholes form and collapse, (2) the instrument is measuring the actual level at a specific time and location in the tank, and (3) this actual level can be only approximately related to the weight of solids in the tank.

The bulk storage bins contained a considerable amount of solids at the end of the injection. Thirty truck loads of solids were removed from the four storage bins: 2 loads from bin 3, 2 loads from bin 4, 12 loads from bin 1, and 14 loads from bin 2. Since each truck load is estimated to contain about 1000 kg (2200 lb) of solids, the total weight of solids remaining after the injection is estimated to be 30,000 kg (66,000 lb). The net consumption of solids was 246,000 kg (540,000 lb).

The mix ratio (the weight of dry solids mixed with each gallon of waste solution or water) is automatically determined during the injection by dividing the reading of the mass flowmeter (lb/min) by the reading of the turbine flowmeter (gpm). The accuracy of this ratio is, of course, dependent on the accuracy of the individual readings (which in the case of the mass flowmeter were suspect during a large part of the injection). A check on the mass flowmeter readings is provided by the ratio of grout volume to solution volume. This ratio is subject to several possible errors; for example, the flowmeter or stroke counter may be misread, the relationship of the volume ratios to the mix ratio is not well known through the entire range of ratios, the relationship of the ratios may vary somewhat with different batches of waste solution or solids, and any increase or decrease in tub holdup volume between readings would bias the results. Despite these potential errors, the volume ratio is a useful check on the mix ratio calculated from mass flowmeter readings. Three

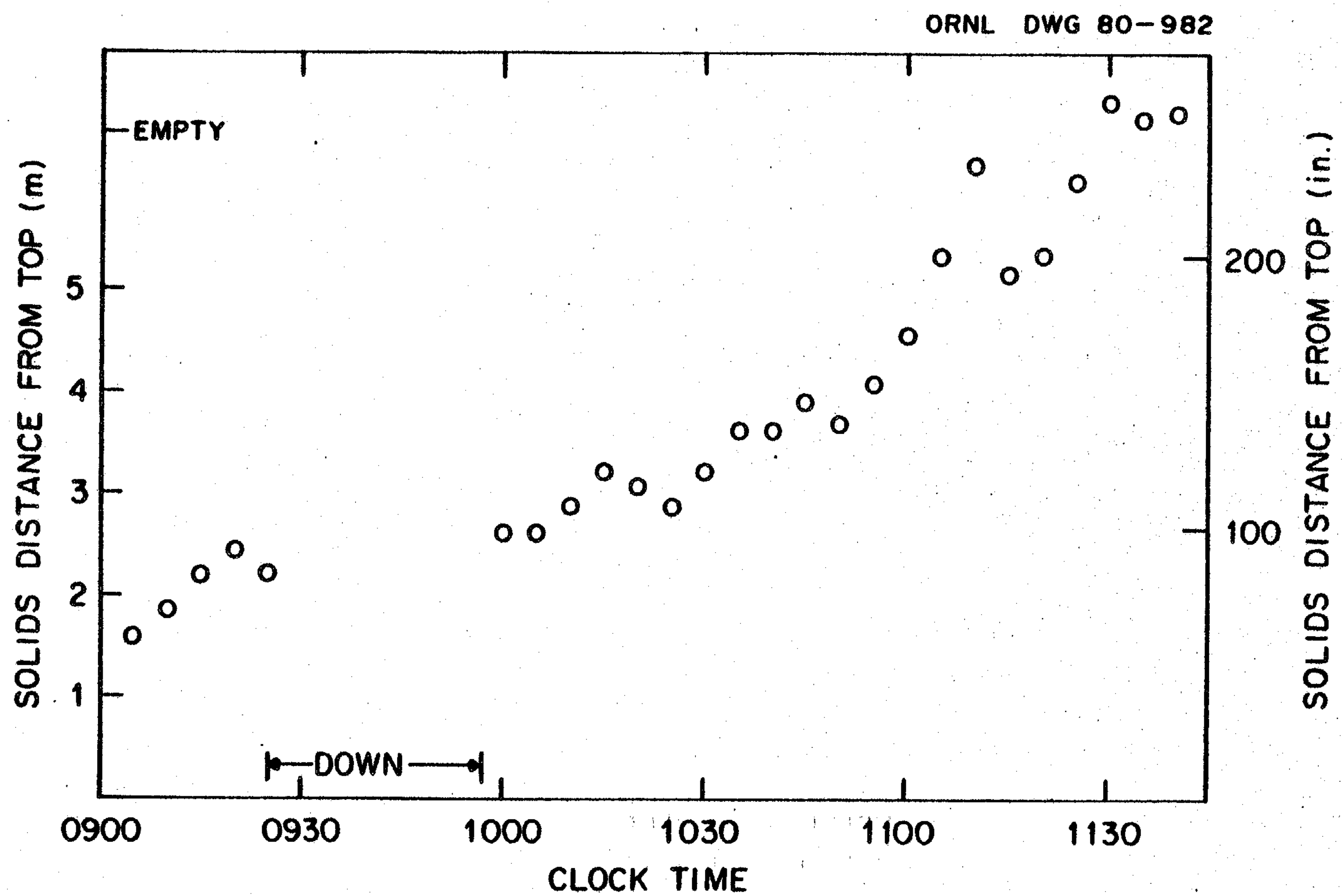

Fig. 12. Monitrol readings showing level indication for bin 3, July 2, 1977.

relationships between the volume ratio and the mix ratio are shown in Figure 13: a calculated relationship based on 100% pump efficiency, a calculated relationship based on 90% pump efficiency, and an observed relationship based on data points from previous injections. The observed relationship was used to calculate solids consumption in Injection ILW-15.

The consumption of solids during various stages of the injection is summarized in Table 6. The values in this table were computed from (1) the weight of solids charged to each bin, (2) the mass flowmeter readings, and (3) the volume ratio.

Washout of the drain valves occurred at about 1440 on June 30. The injection was halted as soon as this situation became known. It was found that pressure could not be maintained in the high-pressure piping manifold by either the injection pump or the standby pump; this would be the case only if more than one valve were leaking. Since the well had to be cleared promptly, a temporary bypass line was connected from the injection pump directly to the wellhead (bypassing the valve rack) and the well was pumped free of grout and shut in. Examination of the high-pressure valves in the valve rack on the following day revealed that three of them were too eroded to hold pressure; therefore, they were replaced.

The results in Table 6 indicate that the mass-meter readings were high. The solids consumption computed from the volume ratio is also high, but the error is smaller and more consistent than that in the mass-meter indications. The source of this error is probably a bias in the curve used to relate the volume ratio to the mix ratio; a similar bias of approximately the same magnitude was noted in Injection ILW-14.

Values for the calculated mix ratio during Injection ILW-15 are given in Figs. 14 and 15. This ratio, which is based on the volume ratio, has been normalized so that the total quantity of solids injected would correspond to the quantity consumed.

The radiation monitor readings showed no clear correlation with the mix ratio and were insensitive to mix fluctuations. Shielding of the monitors to reduce background radiation would probably increase this sensitivity and might improve the results.

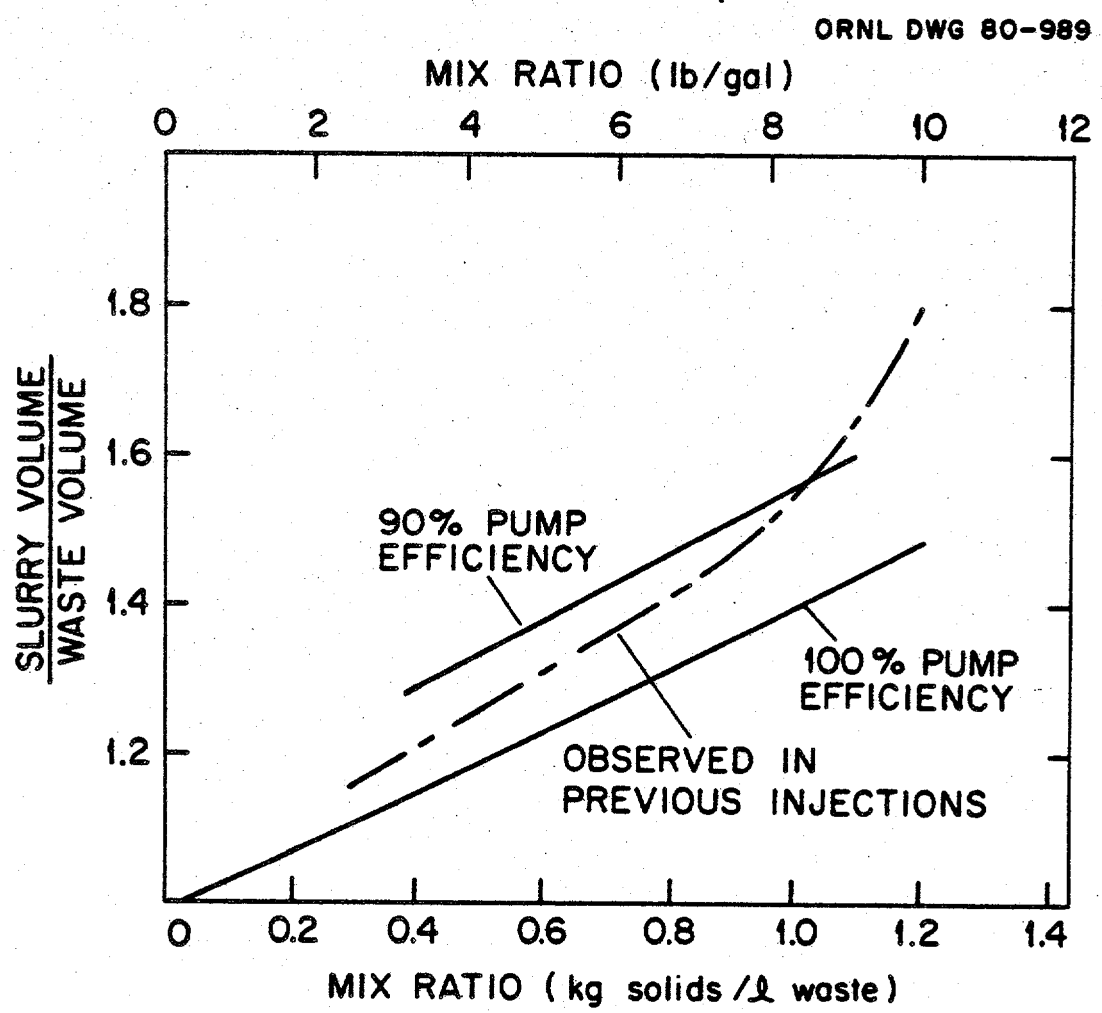

Fig. 13. Corelation between mix ratio and volume ratio.

Table 6. Solids consumption, in kg (lb), during Injection ILW-15

Bin No.	Weight charged	Weight remaining	Weight consumed	Mass-meter indication	Calculated from volume ratio
1	56,200 (123,600)	12,300 (27,000)	44,100 (97,000)	56,800 (124,900)	33,900 (74,500)
2	56,200 (123,700)	1,820 (4,000)	54,600 (120,000)	91,800 (201,900)	69,400 (152,700)
3	54,600 (120,000)	1,820 (4,000)	52,700 (116,000)	68,200 (150,000)	53,200 (117,000)
4	53,000 (116,700)	1,820 (4,000)	51,400 (113,000)	81,900 (180,000)	79,100 (174,035)
2	55,600 (122,400)	12,300 (27,000)	43,200 (95,000)	48,200 (106,100)	37,000 (81,333)

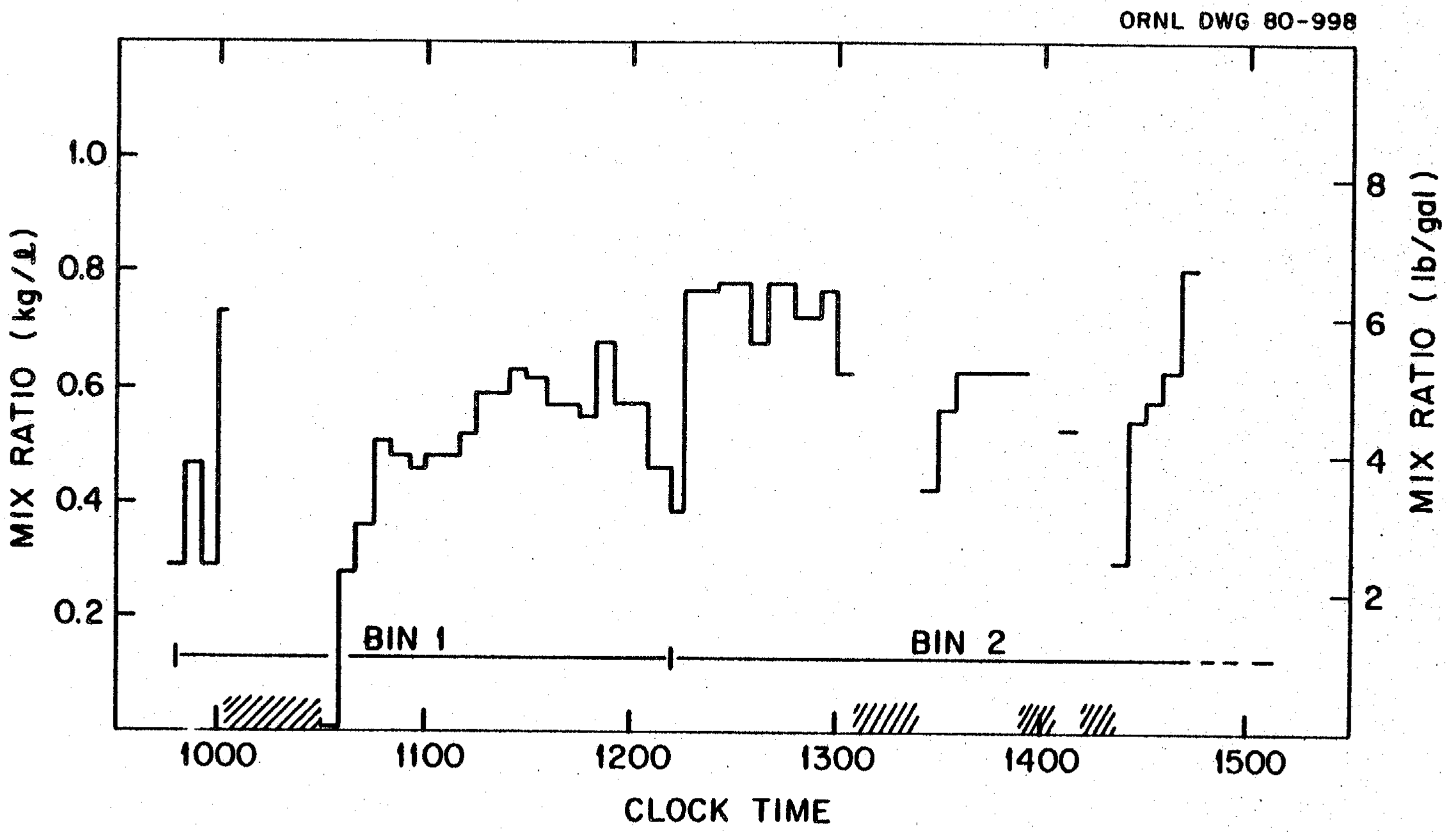

Fig. 14. Corrected mix ratio for Injection ILW-15, June 30, 1977.

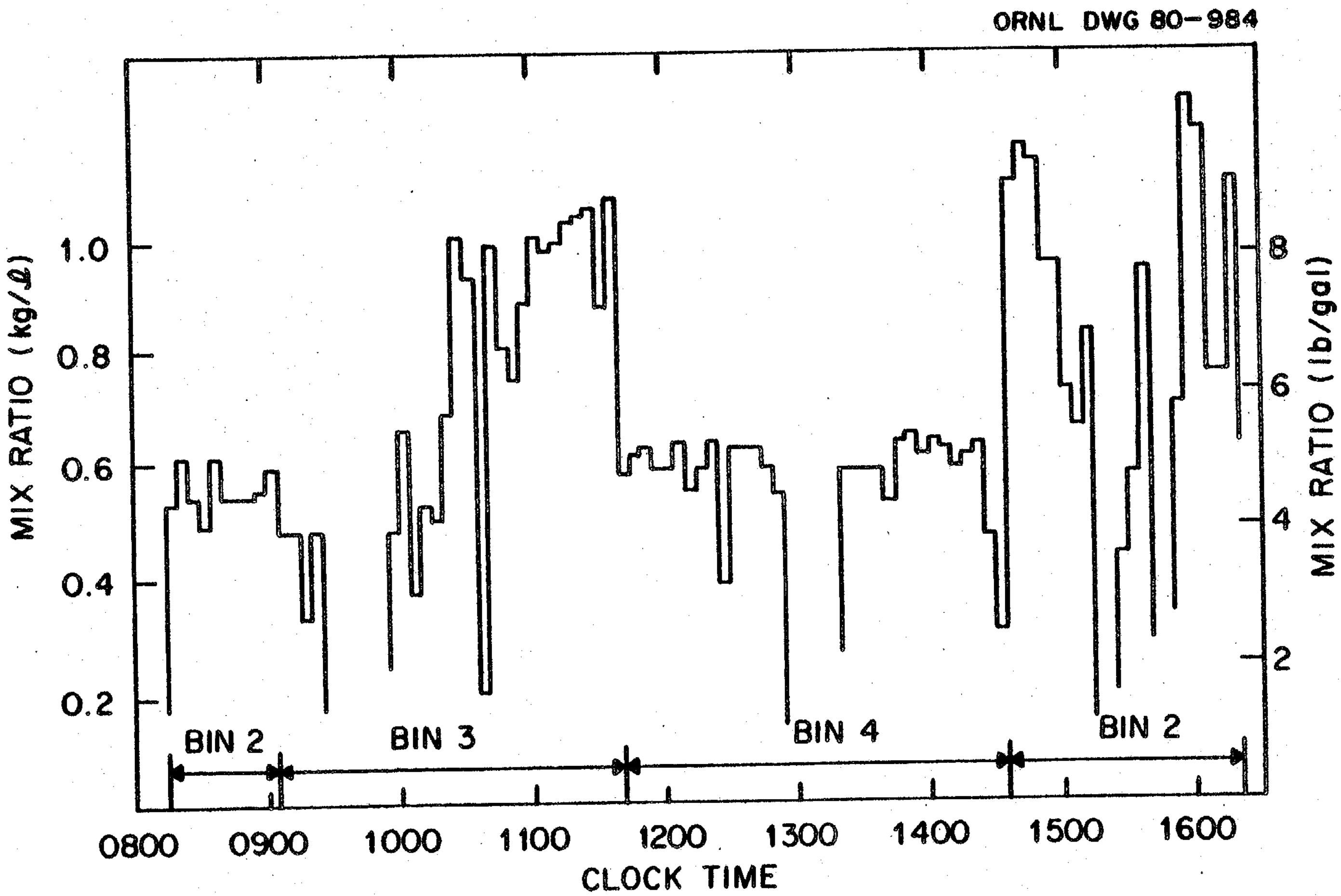

Fig. 15. Corrected mix ratio for Injection ILW-15, July 2, 1977.

3.6 Evaluation of the Injection

More difficulties were experienced during this injection than would normally be expected. These difficulties included an injection pump transmission that periodically malfunctioned, waste pumps that overheated, a frequently erratic mass flowmeter, and a washout of several shutoff valves. More positive aspects included the satisfactory performance of the new lighting system in the mixing tub and a more consistent proportioning of the various dry solids ingredients.

The injection pump transmission obviously did not function well during this injection. Problems with the transmission resulted directly in several interruptions of the injection and indirectly caused several more. During much of the injection, the pump had to be run at a reduced rate; this rate was lower than that required for best operation of the jet mixer and, as a result, a solids buildup frequently occurred in the mixer hopper. One method of clearing these solids was to start and stop the waste pump several times; however, this procedure resulted in overheating of the Moyno waste pumps and either caused or acerbated the problems experienced with these pumps. The frequent stops and starts also probably contributed to the difficulties experienced with the mass flowmeter; in several cases, the stops resulted in the flooding of the bottom of the mixer hopper (and at least the lower part of the mass meter) with waste solution. In the subsequent restart, solids caked on these wetted surfaces. In most cases, the affected area was probably small; however, on some occasions the mass-meter cone was wetted and subsequently became coated with solids; on these occasions the effect on instrument accuracy would be considerable.

Control of the mix ratio was erratic during this injection. A ratio of 0.78 kg/ℓ (6.5 lb/gal) was planned, but the overall average ratio was 0.66 kg/ℓ (5.5 lb/gal), and a portion of the injection was made at a mix ratio well below this average. The primary reason for the difficulty with the control was the biased mass flowmeter readings. Early in the injection, it became obvious that there was a wide discrepancy between the mix ratio, as suggested by the ratio of the pumped volumes and the mix ratio indicated by the mass meter; however, there was reluctance to believe that the error in the mass meter was as great as it actually was. Because bin 1 was never emptied and bin 2 was drawn from on 2 days, no accurate check could be made on the mass meter until bin 3 had been emptied — late in the injection. This check indicated that the mass meter was reading ∿25% high, which was the smallest error noted during the injection, and tended to confirm that an error did exist but was not large.

Keeping the mix ratio comparatively low during an injection provides several advantages; for example, the mechanical problems are fewer with a lean mix, and there is less likelihood of depleting the solids while unused waste solution remains in the tanks. There is no comparable incentive to run with a high mix ratio. When instrument readings indicate different mix ratios in these circumstances, the normal tendency, therefore, is to believe the instrument that shows the higher mix ratio.

In this injection, the ratio of the pumped volumes gave a better indication of the mix ratio than did the mass meter; however, even this indication was ∿11% higher than the actual mix ratio. A similar error was also noted in Injection ILW-14; the calibration curve for this indication should probably be redrawn. Since this ratio provides a useful check on the accuracy of the mass meter, these readings should continue to be taken and computed during an injection.

The level measurements on the storage bins were too erratic to be used for a check on the mix ratio; a weight measurement was needed. The strain gage on bin 1 performed satisfactorily (except for a zero error), as it had in previous injections. The other strain gages, which have a history of unreliability, did not function properly during this injection.

The new lighting system in the mixing tub worked quite well; this perennial problem appears to have been solved.

The proportioning of the dry solids was much better for this injection than for previous injections. Only the first bin that was blended had an appreciably different composition from the standard mix.

3.7 Post-Injection Operations

The pressure at the injection well was 4.59 MPa (665 psi) on July 6, 1977. The rate of pressure decrease was proportional to the logarithm of time until the bleedback operation was started and the pressure observation was stopped. The final observed pressure was 2.14 MPa (310 psi).

Bleedback from Injection ILW-15, which was started on August 22, 1977, and continued until October 11, amounted to a total of 6170 ℓ (1630 gal). The initial rate was 16.3 ℓ/h (4.3 gal/h), while the final rate was less than 1.1 ℓ/h (0.30 gal/h). Figure 16 is a plot of the recovered bleedback volume. This rate of bleedback is quite low in comparison to previous measurements.

The observation wells were logged. No trace of the injection was found in wells S-220, E-320, NW-100, or N-200. Minor peaks were noted in wells N-100 and N-150 at 244 m (801 ft) and 249 m (817 ft) respectively. Three peaks were observed in well N-125 at 247 m (810 ft), 247.2 m (811 ft), and 248 m (815 ft).

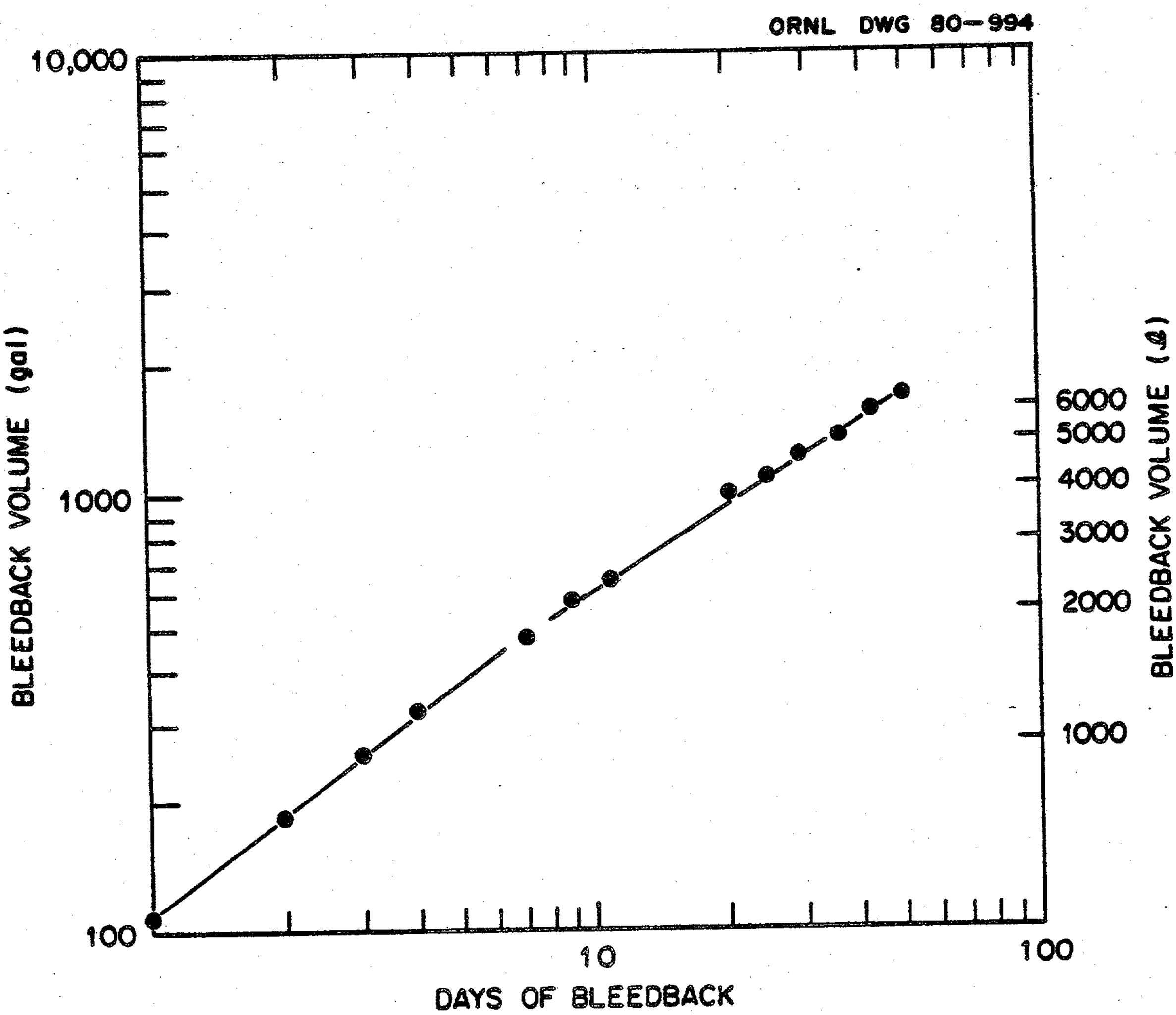

Fig. 16. Volume of bleedback recovered after Injection ILW-15.

4. INJECTION ILW-16

4.1 Preliminary Preparations

4.1.1 Waste transfer and analysis

A proportional sample of the waste solution to be injected is routinely obtained as the solution is pumped from the waste storage tanks in Bethel Valley to the waste storage tanks at the shale fracturing site. The sample is obtained only shortly before the injection, however, and an earlier analysis is needed for mix compatibility tests. For this reason, a grab sample from one of the waste storage tanks in Bethel Valley was analyzed for this injection. The analyses of both samples are given in Table 7. As seen, the results are similar for soluble components but dissimilar for insoluble components.

The filled tank volumes were as follows: T-1, 55,910 ℓ (14,772 gal); T-2, 56,320 ℓ (14,881 gal); T-3, 92,900 ℓ (24,545 gal); T-4, 94,530 ℓ (24,975 gal); and T-9, 48,890 ℓ (12,918 gal).

4.1.2 Facility modifications

One measure of the mix ratio during an injection (and a useful check on the mass meter) is the ratio of grout volume to waste volume. In injections prior to ILW-16, this ratio had been calculated at 5-min intervals from readings taken from the stroke counter and the turbine flowmeter. For Injection ILW-16, an instrument was devised to provide an indication of the instantaneous value of this ratio. A recorded tracing of this ratio was planned, but the recorder was not available in time for the injection.

The floats on the Monitrol solids level measuring devices were firmly attached to the cables. Safety lines were also provided.

4.1.3 Preliminary maintenance

Shortly after the completion of Injection ILW-15, the solids remaining in the bins were removed and disposed of. The bins and the mass-meter cone were cleaned, and the mass meter was reworked.

Table 7. Composition of waste solution for Injection ILW-16

Component	Grab sample	Proportional sample
NO_3^-, M	0.635	NA[a]
NH_4^+, M	1.5×10^{-5}	NA
Al^{3+}, M	0.029	NA
K^+, M	0.178	NA
Na^+, M	2.575	NA
CO_3^{2-}, M	0.34	NA
OH^-, M	0.49	NA
Cl^-, M	0.039	NA
SO_4^{2-}, M	0.119	NA
Specific gravity	1.1676	NA
^{137}Cs, Ci/ℓ (Ci/gal)	0.065 (0.247)	0.072 (0.271)
^{90}Sr, Ci/ℓ (Ci/gal)	9.8×10^{-5} (3.7×10^{-4})	7.7×10^{-3} (0.0293)
^{60}Co, Ci/ℓ (Ci/gal)	9.0×10^{-4} (3.4×10^{-3})	1.0×10^{-3} (3.9×10^{-3})
^{134}Cs, Ci/ℓ (Ci/gal)	5.3×10^{-4} (2×10^{-3})	4.1×10^{-4} (1.55×10^{-3})
^{106}Ru, Ci/ℓ (Ci/gal)		3.2×10^{-4} (1.2×10^{-3})
α Ci/ℓ (Ci/gal)	5.9×10^{-6} (2.25×10^{-5})	9.6×10^{-7} (3.64×10^{-6})
^{238}Pu, Ci/ℓ (Ci/gal)	8.5×10^{-7} (3.2×10^{-6})	
^{244}Cm, Ci/ℓ (Ci/gal)	4.0×10^{-6} (1.5×10^{-5})	
^{242}Cm, Ci/ℓ (Ci/gal)		9.6×10^{-7} (3.64×10^{-6})

[a]NA = not analyzed.

During the 3 days prior to the injection, several maintenance tasks were completed. For example, the valves in the high-pressure system were cleaned and checked and several cores and inserts were replaced. In addition, the remote transmission shifter was connected. Four of the valve seats on the injection pump were replaced, the pump was repacked, and the new packing was "run-in." Examination of the suction hoses to the injection pump revealed that they were cemented. Therefore, the cement was removed from one hose, and the second hose was replaced. The mass meter was repaired and calibrated.

4.1.4 Plugging and slotting injection well

Four injections had been made into the existing slot at 250 m (822 ft); operating procedures require that the existing slot be plugged and a new slot be cut at a depth 3 m (10 ft) above the previous slot. On November 14, a batch of cement grout was mixed and pumped into the well. This grout was displaced with 215 gal of water and the well was shut in under pressure. On November 15, the plug failed when tested under pressure. The plugging operation was then repeated with a second batch of cement slurry, which was displaced with 795 ℓ (210 gal) of water. On November 16, the plug held at a pressure of 34.5 MPa (5000 psi). When the depth of the plug was measured, 246 m (806 ft), it was found to be 1.8 m (6 ft) too high. Therefore, the plug was drilled out to 248 m (814 ft).

The well was slotted at 247.5 m (812 ft), using pressure that varied between 31 and 17 MPa (4500 and 2500 psi) at about 570 ℓ/min (150 gpm). Thirty-five sacks of sand and 22.7 kg (50 lb) of WG-6 suspender were used. The well was pressured to 34.5 MPa (5000 psi) but would not break; a pressure of 37.9 MPa (5500 psi) was required. The slot was enlarged by pumping ∿7600 ℓ (2000 gal) of water. The injection pressure gradually decreased during this period from 37.9 to 33.1 MPa (5500 to 4800 psi), while the injection rate increased from 380 to 760 ℓ/min (100 to 200 gpm).

4.1.5 Solids blending

Five batches of dry solids were blended and loaded in the storage bins at the fracturing site. Four of these were loaded in the storage bins, while the remaining one was left in the blending tanks for later transfer to an empty bin. The weights of the various ingredients that were used for the solids mix are given in Table 8.

It has been observed previously that the effectiveness with which the grouts made from the blended solids will retain water varies inversely with the number of blending transfers to which the solids are subjected. Blending operations in the laboratory are comparatively gentle, and a ratio of 0.72 kg of dry mix per liter of waste (6 lb/gal) is almost always sufficient to bind all the water. Blending operations in the field are more rigorous, and a ratio of at least 0.84 kg/ℓ (7 lb/gal) is usually required. Results of the solids compatibility testing for recent injections show that the blended solids in the P-tank (which had been subjected to one less blending transfer) would bind more waste per unit weight than the solids in the various storage bins. In this injection, therefore, a test was desired to determine whether one of the four blending transfers could be eliminated without adverse effects on mix quality. For this test, the solids in storage bin 1 were to be transferred one time fewer than the solids in the other storage bins and any differences in viscosity or phase separation noted. This was essentially done as planned, although a failure of the bag solids conveyer at the start of the blending operation complicated the procedure.

The conveyer failed after the trucks containing that day's supply of cement and fly ash had already arrived. Repairs to the conveyer would require such a large portion of the day that no time would be left for blending operations; on the other hand, the truck operators wanted their trucks emptied as expeditiously as possible. Accordingly, the contents of the trucks were transferred into the pressure tanks, one-third of the cement and one-third of the fly ash being charged to each tank. The following day (after the conveyer had been repaired), the other ingredients were added to the cement and fly ash in the scale tank, and these solids were blended and transferred to the storage bin. This procedure was repeated for the materials stored in the other two pressure tanks.

The overall result was that the cement and fly-ash components of the mix were transferred more times than usual; however, the mix as a whole was subjected to one less transfer than required by the normal blending

Table 8. Dry solids mix for Injection ILW-16

	Bin 1	Bin 2	Bin 3	Bin 4	P-tanks
Blending date	11/10/77	11/11/77	11/8/77	11/7/77	11/14/77
Cement, kg (lb)	22,070 (48,560)	21,400 (47,070)	21,830 (48,030)	21,800 (47,950)	21,250 (46,740)
Fly ash, kg (lb)	23,210 (51,070)	26,050 (57,300)	24,290 (53,430)	22,705 (49,950)	23,910 (52,600)
Attapulgite, kg (lb)	8,750 (19,250)	8,800 (19,360)	8,740 (19,220)	8,800 (19,360)	8,405 (18,490)
Clay, kg (lb)	4,380 (9,630)	4,470 (9,830)	4,450 (9,800)	4,640 (10,212)	4,230 (9,310)
Sugar, kg (lb)	25 (54)	25 (54)	25 (54)	25 (54)	25 (54)
Total	58,438 (128,564)	60,730 (133,614)	59,330 (130,534)	57,970 (127,526)	57,815 (127,194)

procedure (except for the first batch transferred to the storage bin; the treatment of this batch was necessarily anomalous). Transfers of cement or fly ash are not considered to have any influence on mix properties; however, it is believed that transfers of attapulgite have a marked effect. The improvised blending procedure could therefore serve to confirm or deny this belief.

The following materials were used in this injection: cement, Penn-Dixie Type I; fly ash, supplied by the Southeast Fly Ash Company; attapulgite, Attapulgite 150 drilling clay; clay, "Indian Red" pottery clay, supplied by the American Art Clay Company; sugar, delta gluconolactone.

4.1.6 Tests of mix compatibility

Samples of the blended dry solids from each of the storage bins and the second pressure tank were tested with synthetic waste solutions. A few tests were also made with water. Phase separation and rheological properties were determined for grouts made with various mix ratios. Most of the tests were made with grouts that were prepared by mixing the dry solids and waste solution at both 5000 rpm (to stimulate down-hole conditions) and 2000 rpm (to stimulate tub conditions). The samples from bins 2, 3, and 4 were much like those tested for Injection ILW-15; they were quite fluid, even at mix ratios of 1.08 kg/ℓ (9 lb/gal), and little difference was observed between the characteristics of the grouts sheared at 2000 rpm and those sheared at 5000 rpm. The phase separation of these grouts was ∿2% at 0.96 to 1.08 kg/ℓ (8 to 9 lb/gal). The "apparent viscosity" was ∿30 cP at 0.96 kg/ℓ (8 lb/gal) and 50 cP at 1.08 kg/ℓ (9 lb/gal). However, grouts made from bin 1 and pressure tank samples had appreciably different characteristics. The phase separation of these grouts was <2% at 0.84 kg/ℓ (8 lb/gal), and the "apparent viscosity" was ∿35 cP at 0.84 kg/ℓ (7 lb/gal) and 50 cP at 0.96 kg/ℓ (8 lb/gal). The grouts made from solids in these bins at a mix ratio of 0.84 kg/ℓ (7 lb/gal) resembled the grouts made from solids in bins 2, 3, and 4 at a mix ratio of 0.12 to 0.24 kg/ℓ (1 to 2 lb/gal) greater. Mix compatibility data at 5000 rpm are shown in Table 9.

Table 9. Mix compatibility tests for Injection ILW-16[a]
(All tests made at 5000 rpm)

Bin number	Mix ratio (kg/ℓ)	Mix ratio (lb/gal)	Density (kg/ℓ)	Density (lb/gal)	Phase separation (%)	Apparent viscosity (cP)
4	0.84	7	1.45	12.05	4.1	25
	0.96	8	1.47	12.22	1.6	37
	1.08	9	1.50	12.50	1.2	58
3	0.84	7	1.48	12.30	6.4	21
	0.96	8	1.51	12.55	3.2	29
	1.08	9	1.54	12.85	2.7	44
2	0.84	7	1.44	12.0	3.8	22
	0.96	8	1.47	12.25	1.7	35
	1.08	9	1.50	12.50	0.78	56
1	0.84	7	1.43	11.9	1.6	41
	0.96	8	1.48	12.35	0.8	76
P-tank	0.84	7	1.46	12.15	Nil	28
	0.96	8	1.48	12.30	Nil	53

[a]Data obtained from J. G. Moore.

Grouts made with water and the solids in bin 1 had a phase separation of 3% at a mix ratio of 0.84 kg/ℓ (7 lb/gal). The "apparent viscosity" of this grout was ~40 cP under tub conditions.

4.2 Injection

Sufficient solids were on hand to permit the injection of 333,100 ℓ (88,000 gal) of waste [leaving a heel of 3030 ℓ (800 gal) in each tank] and 18,900 ℓ (5000 gal) of water at a mix ratio of very nearly 0.84 kg/ℓ (7 lb/gal). Tests of the blended solids had indicated that considerable phase separation would be expected to occur at this mix ratio. The relevance of the phase separation tests to the underground situation (in which the grout sets under considerable pressure) is in some doubt, however, and the 0.84 kg/ℓ (7 lb/gal) mix ratio was chosen for this injection.

Prior to the injection, the fracture was reopened and expanded by pumping water through the fracture. The fracture was reopened at a pressure of 37.9 MPa (5500 psi) and a flow rate of 380 ℓ/min (100 gpm); after several minutes, the rate was increased to 760 ℓ/min (200 gpm) and the pressure had dropped to 33.1 MPa (4800 psi). Approximately 7600 ℓ (2000 gal) of water was pumped.

The injection was begun at 0922 on November 17, 1977. Since no appreciable solids flow could be obtained from any of the four bins, the injection was temporarily halted to correct this situation. Solids flow was started from bin 1, and the injection was resumed at 0927 with waste from tank T-3. The initial injection pressure was just under the 34.5-MPa (5000-psi) operating limit; to keep the pressure from exceeding this limit, the injection pump was operated at a lower-than-usual volumetric rate — ~720 ℓ/min (190 gpm). Plots of the injection pressure (wellhead measurement) and waste flow rate throughout the injection are shown in Figs. 17 and 18. The flow rate readings are average values (usually over a 5-min period) indicated by the turbine flowmeter.

The mix ratio during the injection was obtained by dividing the solids flow indicated by the mass meter by the liquid flow indicated

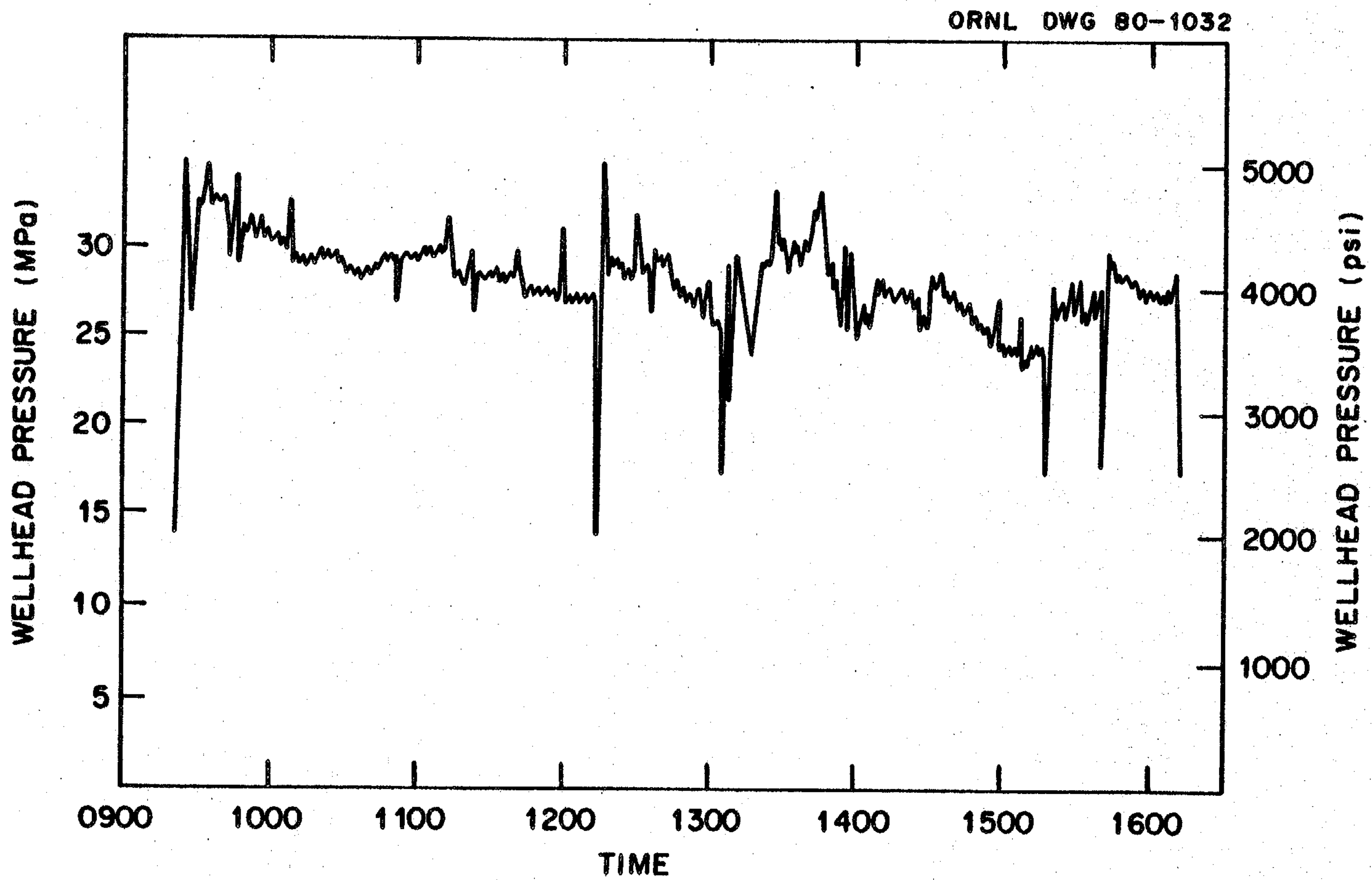

Fig. 17. Wellhead pressure measurements during Injection ILW-16.

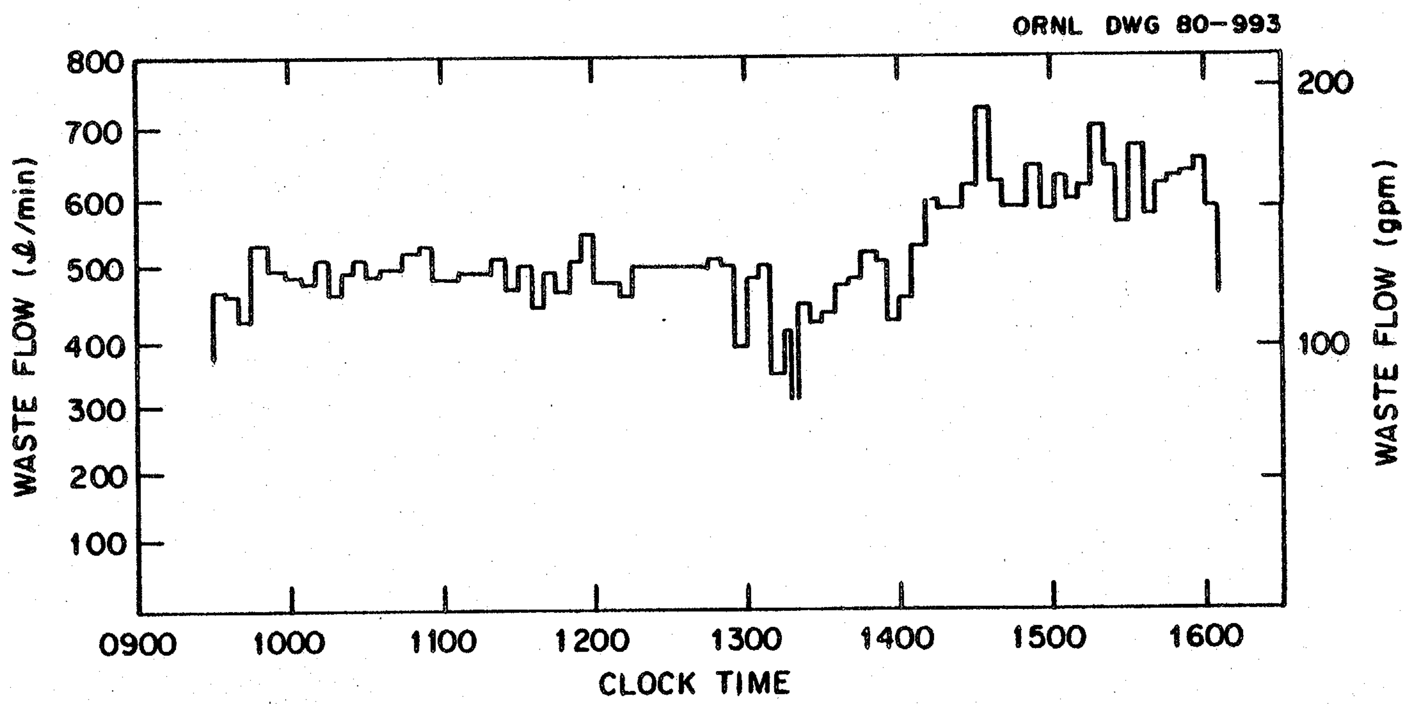

Fig. 18. Waste solution flow rates for Injection ILW-16.

by the turbine flowmeter. A check on this mix ratio was obtained by dividing the volume of grout pumped over a short time interval (measured by the stroke counter on the injection pump) by the volume of waste pumped over the same interval and using the correlation shown in Fig. 13 to relate the volume ratio to the mix ratio. The upper line of the correlation (90% pump efficiency) was used in all volume ratio calculations for this injection.

During the injection, the mix ratio was calculated at 5-min intervals from both mass-meter and volume ratio indications and compared. This comparison is shown in Fig. 19. Starting about 1000 h, a consistent difference between the mass-meter and volume ratio indications is evident. This difference could have resulted from a solids buildup on the mass-meter sensing cone, an error in the turbine flowmeter reading, the use of the wrong volume ratio correlation, or some unsuspected factor. Since the difference was not large enough to be really significant and was not increasing, no corrective action was taken.

At 1044, solids flow became erratic and was switched to bin 3. All instruments (strain gage reading, level reading, mass-meter reading, and volume ratio readings) indicated that a considerable quantity of solids still remained in bin 1; therefore the solids flow was switched back to bin 1. The flow remained somewhat erratic and was switched several times before it stabilized and the remaining bin contents could be withdrawn. Finally, the flow was switched to bin 3 at 1130.

At 1245, the mass meter stopped functioning. From this time until the end of the injection, the only available measurement of the mix ratio was that derived from the volume ratio. Because this measurement was an "after-the-fact" measurement, it gave an average value of what the mix ratio had been; it did not give an instantaneous value of the mix ratio at a particular moment. (The experimental ratio indicator that could have given such an instantaneous value had developed a considerable bias and could not be trusted.) Estimation of the mix ratio from visual observation of grout in the mix tub was found to be unreliable. Only very thick (>1.2 kg/ℓ (10 lb/gal) or very thin [<0.24 kg/ℓ (2 lb/gal)] grouts could be recognized; all concentrations between these extremes appeared to be essentially the same. The method of mix control that was

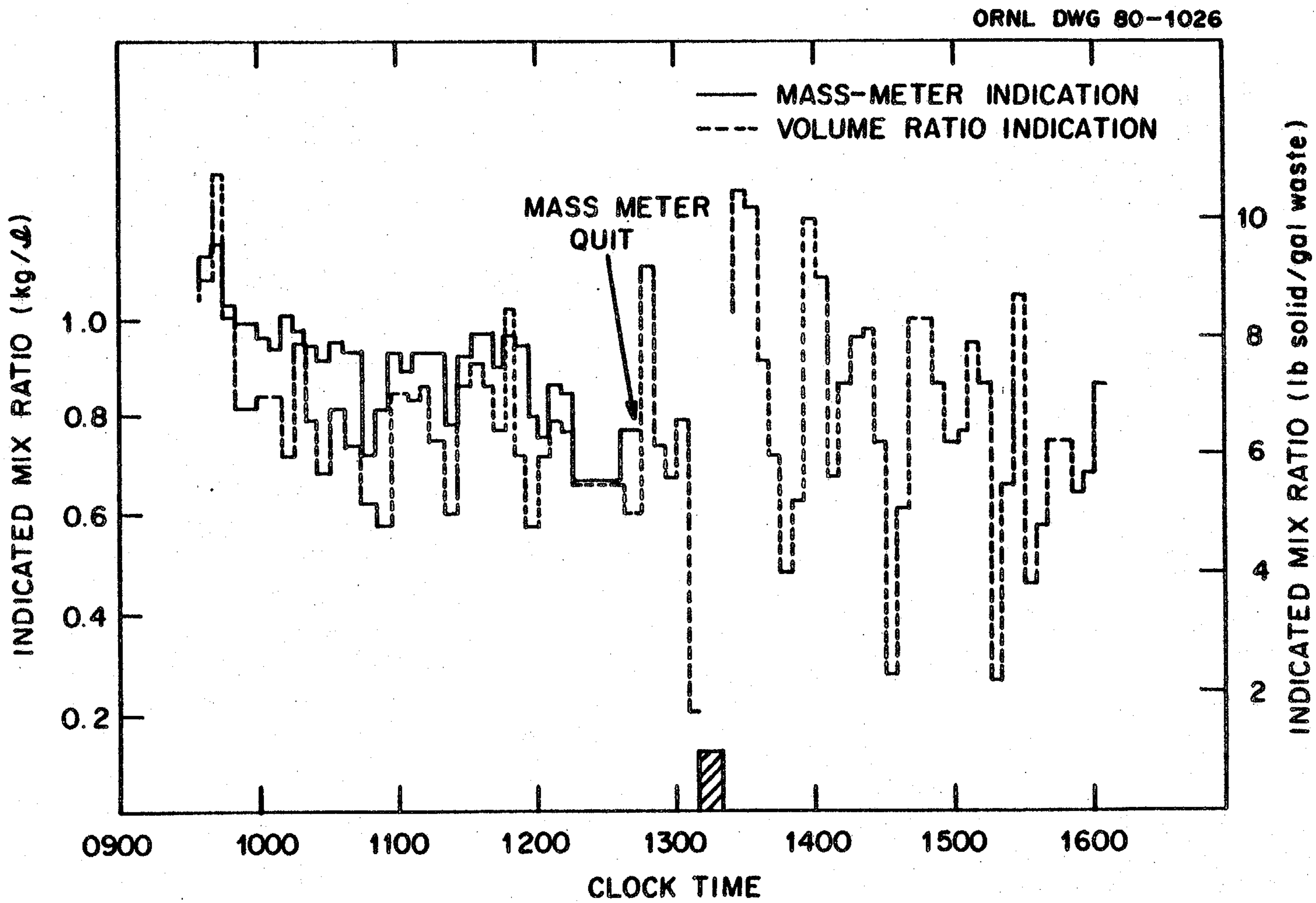

Fig. 19. Indicated mix ratios for Injection ILW-16.

improvised for the remainder of the injection was to change the solids flow control valve as little as possible, to make changes to the setting only if the grout appeared too thick or too thin or if a volume ratio reading indicated that a change was desirable. The resulting control of the mix ratio was rather erratic, as can be seen in Fig. 19. Generally, a fairly constant mix ratio could be maintained for 20 to 30 min, then an adjustment would overcorrect and the grout would become quite thin or quite thick. These fluctuations averaged out over a period of time, however, and the average mix ratio was about 0.73 kg/ℓ (6.1 lb/gal).

At 1308, the injection was interrupted because the window of the solids hopper had become completely obscured with dust. After the window had been washed, the injection was restarted (at 1310); however, it was necessary to halt the injection again and wash the hopper in order to effect solids flow. The injection was restarted at 1320.

By 1400, the injection pressure had fallen to about 27.6 MPa (4000 psi) and the injection rate could be increased. During the final 2 h of the injection, the injection rate averaged 870 ℓ/min (230 gpm of slurry [610 ℓ/min (161 gpm) of waste].

At 1610, the injection pump diesel threw a connecting rod through the block. The standby pump was used to wash the well and to pump the slot clear of grout. The well was valved shut, and the equipment was washed. The injected waste volume was 208,924 ℓ (55,198 gal); the total amount of solids consumed was 178,200 kg (392,000 lb).

The pressures in the rock cover wells were read prior to the injection and at intervals during the injection. These readings are given in Table 10. An appreciable pressure change was noted in several wells.

4.3 Data Analysis

The volume of waste solution or pit water pumped during this injection was measured by three methods. The solution flow to the mixer was measured by a turbine flowmeter as well as a recording orifice meter. The volume of waste solution that was pumped out of the waste storage tanks was measured by the change in tank solution level.

Table 10. Pressure readings, in kPa (psig), for rock cover wells — Injection ILW-16

Rock cover well	Pre-Injection	Reading taken on November 17, 1977, at:				
		1020	1210	1335	1500	1635
E-300	83 (12)	76 (11)	69 (10)	48 (7)	48 (7)	103 (15)
NE-125	0	141 (20.5)	131 (19)	148 (21.5)	186 (27)	221 (32)
NE-200	-21 (-3)	41 (6)	21 (3)	21 (3)	7 (1)	24 (3.5)
N-200	-41 (-6)	-7 (-1)	-3.5 (-0.5)	-3.5 (-0.5)	-34 (-4.9)	-48 (-6.9)
N-275	13.8 (2)	24.1 (3.5)	3.5 (0.5)	0	-3.5 (-0.5)	-3.5 (-0.5)
NW-175	-17 (-2.5)	-10.3 (-1.5)	276 (40)	355 (51.5)	303 (44)	269 (39)
NW-250	41 (6)	27.6 (4)	200 (29)	379 (55)	393 (57)	362 (52.5)
W-300	0	0	0	0	0	0
S-200	131 (19)	131 (19)	121 (17.5)	128 (18.5)	300 (43.5)	293 (42.5)

All three measurements gave essentially the same results (within ∿5%). In the time interval between 1320 and 1448, for instance, the tank level measurements indicated that 49,542 ℓ (13,089 gal) of waste had been pumped, the turbine flowmeter indicated 47,150 ℓ (12,457 gal), and the orifice meter indicated 46,574 ℓ (12,305 gal). A section of the orifice meter recorder chart is shown in Fig. 20 to indicate the normal flow fluctuations that occur during all injections but are obscured in the average values that are usually reported. Because the turbine meter readings are generally more convenient to use than the tank level readings or the orifice meter readings, they are used in the subsequent calculations.

The volumes of grout that were injected were measured by the stroke counter on the injection pump. These volumes were recorded at 5-min intervals.

Bin levels (plumb bobs) and bin weights (strain gages) on bins 1 and 3 were also noted at intervals. Bin 2 has no usable level or weigh gage installed, and the injection was completed before the contents of bin 4 were used.

The strain gage on Bin 1 functioned satisfactorily in this injection, as it had in all previous ones. At 1130, when the bin was finally judged to be empty, the strain gage indicated <5% solids remaining. The comparatively few plumb bob readings taken on this bin indicated a solids level ∿20% higher than the strain gage readings.

The bulk storage bins contained a considerable amount of solids at the end of the injection. Bin 1, which had been refilled with the solids stored in the blending tanks, was full; bin 4 was full; bin 2 was empty, and bin 3 contained an estimated 450 kg (1000 lb).

The mix ratio (the weight of dry solids mixed with each volume of waste solution or water) is automatically determined during the injection by dividing the reading of the mass flowmeter by the reading of the turbine flowmeter. This ratio is recorded. A check on the mass flowmeter readings is provided by the ratio of grout volume to solution volume. This ratio was calculated at 5-min intervals during the injection and converted to a mix ratio by means of the correlation shown in Fig. 13. A plot of both of these mix ratios is shown in Fig. 19. A comparison of these mix ratios indicates that during the time the mass meter was working

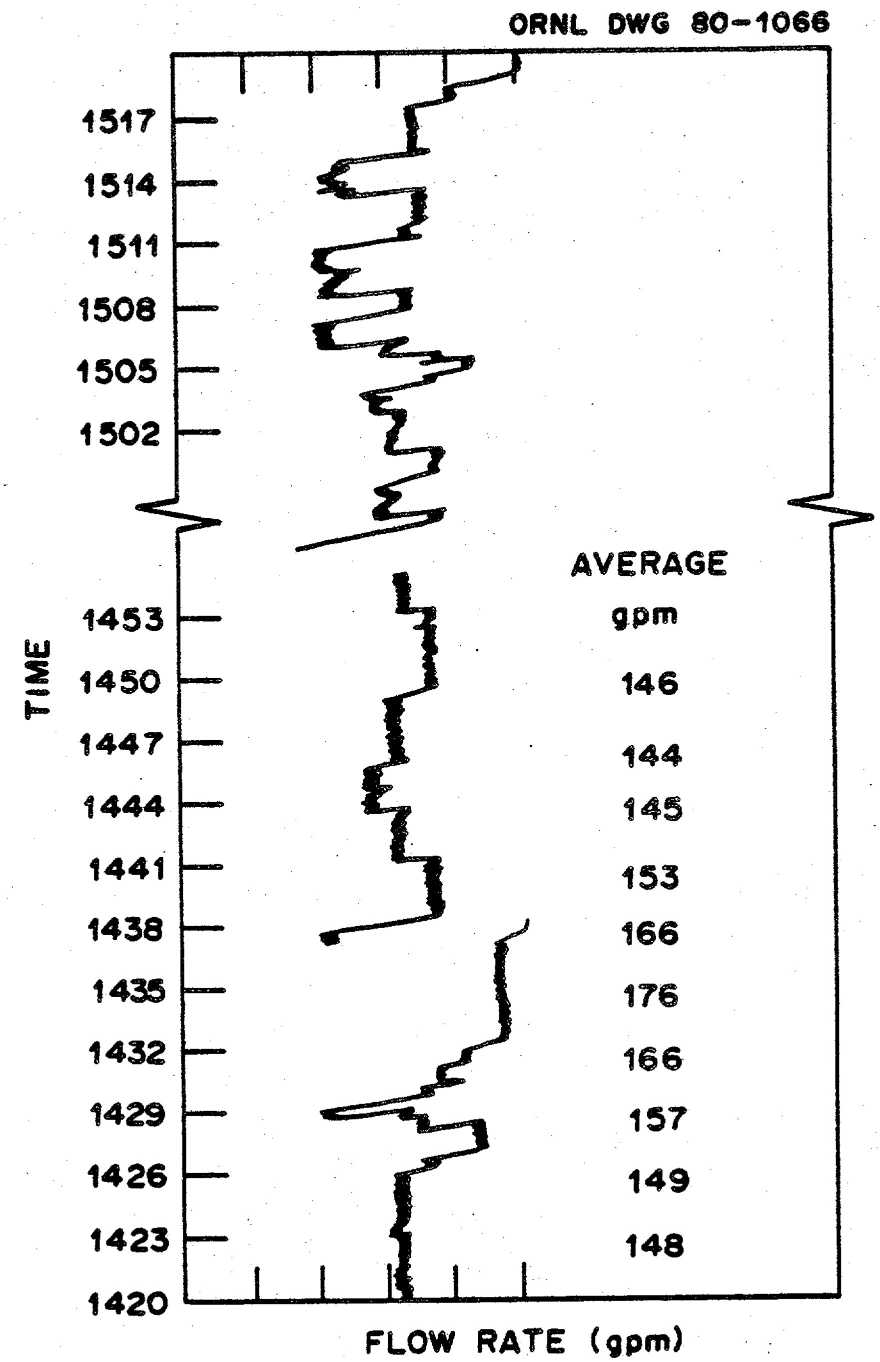

Fig. 20. Waste flow rates as indicated by orifice meter during Injection ILW-16.

it was indicating a mix ratio from 5 to 15% higher than that calculated from the volume ratios. For this injection, the mix ratio calculated from the mass-meter readings correlates better with the measurements of solids consumption than does the mix ratio calculated from the volume ratio; therefore, it appears that the mass-meter mix ratio was the correct one during the first half of the injection. During the later part of the injection (when the mass meter was inoperable), however, the mix ratio calculated from the volume ratio checked very closely with the quantity of solids withdrawn from bin 2 and is thus probably very nearly correct. Until 1245, therefore, the mix ratio averaged ~0.86 kg/ℓ (7.2 lb/gal); from 1245 until the end of the injection, it averaged ~0.84 kg/ℓ (7.0 lb/gal).

4.4 Evaluation of the Injection

The diesel drive of the injection pump failed about two-thirds of the way through Injection ILW-16. In addition, other problems were encountered: (1) there was difficulty in starting the flow of solids from the bins, (2) the mass meter stopped functioning approximately one-third of the way through the injection, and (3) the injection pressure was uncomfortably high throughout the entire operation. Until the final pump failure, however, this injection generally ran more smoothly than did previous ones. Positive aspects were the satisfactory performance of the waste pumps, lack of transmission problems with the injection pump, and acceptable control of the mix ratio (quite good in the first half of the injection and adequate in the second half).

Determination of the mix ratio from the ratio of pumped volumes is clearly a useful check on the mass meter and a vital emergency backup. An instantaneous reading and recording of the volume ratio would have been useful during this injection since they would have permitted much more precise control of the mix ratio during the last half of the injection (after the mass meter had failed). Provision for these readings will be made for Injection ILW-17.

The solids in bin 1 that had been blended one time less than the solids in bins 2-4 flowed almost as easily and mixed as readily as those in the other bins. A reduction in the number of blending transfers simplifies the blending procedure somewhat, improves the mix properties appreciably, and appears to have no effect on bulk flowability.

Some difficulty was experienced in starting the solids flow from each of the bins. The reason for this difficulty is not known.

4.5 Post-Injection Operations

The pressure at the injection well dropped from 4738 kPa (687 psi) at 18 h after the injection had been completed to 297 kPa (43 psi) at 18 days after the injection. This rate of pressure fall is much more rapid than that observed after Injection ILW-15. The values measured for Injection ILW-16 are given in Table 11.

A bleedback operation was attempted, but no water was recovered.

All of the observation wells, except NE-125, were logged. No trace of the injection was seen in E-300; however, minor peaks were noted in wells N-100 and NW-100 at 232 m (763 ft) and 230 m (754 ft) respectively. An enlargement of an existing peak was observed in S-220 at 240 m (788 ft). A new peak was seen in N-150 at 239 m (783 ft). The cap on well NE-125 had been broken by freezing, and a small volume of contaminated water had leaked from the well. Therefore, this well was not logged.

Table 11. Wellhead pressure readings after Injection ILW-16

Time (days)	Pressure (kPa)	Pressure (psi)
0.75	4738	687
1	4497	652
4	1897	275
11	897	130
14	441	64
15	414	60
18	297	43

5. INJECTION ILW-17

5.1 Preliminary Preparations

5.1.1 Waste transfer and analysis

The waste solution to be injected was accumulated in tanks W-8 and W-10 in Bethel Valley. The volumes in these tanks were 114,000 ℓ (30,000 gal) and 189,000 ℓ (50,000 gal) respectively. A grab sample of the solution in each of these tanks was taken and analyzed for radiochemical constituents. The results are given in Table 12. No chemical analyses of the waste solution were made for this injection.

The filled tank volumes were as follows: T-1, 55,912 ℓ (14,772 gal); T-2, 56,325 ℓ (14,881 gal); T-3, 92,445 ℓ (24,424 gal); T-4, 93,414 ℓ (24,680 gal); and T-9, 49,205 ℓ (13,000 gal).

5.1.2 Facility modifications

A new diesel engine was provided for the injection pump [Cummins VT-1710 C, 470 kW (630 hp) at 2100 rpm].

An arrangement of air pads was installed on each of the bulk storage bins. Sixteen pads, 19 cm (7-1/2 in.) by 9.5 cm (3-3/4 in.) overall, were installed on each bin at four levels: 25 cm (10 in.) from the bottom outlet (measured along the side of the cone), 63 cm (25 in.), 102 cm (40 in.), and immediately below the junction between the cone and the vertical sides [3 m (10 ft) from the bottom outlet]. The pads in the bottom three levels were aligned vertically while those in the top level were staggered. Air was supplied to each vertical row of four pads at 0.71 m^3/min (25 cm) and 20.7 kPa (3 psi). Figure 21 illustrates the arrangement of two sets of pads.

A recorder was obtained for the volume ratio (volume of grout per volume of waste) measurement.

Table 12. Composition of waste solution for Injection ILW-17

Component	Tank W-8 (Ci/ℓ)	Tank W-8 (Ci/gal)	Tank W-10 (Ci/ℓ)	Tank W-10 (Ci/gal)
^{60}Co	7.9×10^{-4}	3.0×10^{-3}	6.3×10^{-4}	2.4×10^{-3}
^{134}Cs	8.5×10^{-4}	3.2×10^{-3}	2.6×10^{-4}	1.0×10^{-3}
^{137}Cs	8.2×10^{-2}	3.1×10^{-1}	6.8×10^{-2}	2.6×10^{-1}
^{90}Sr	3.0×10^{-4}	1.0×10^{-3}	3.2×10^{-4}	1.2×10^{-3}
^{106}Ru	3.1×10^{-3}	1.2×10^{-2}	None	None
^{244}Cm	None	None	1.19×10^{-5}	4.5×10^{-5}
$^{239-240}Pu$	6.3×10^{-7}	2.4×10^{-6}	None	None

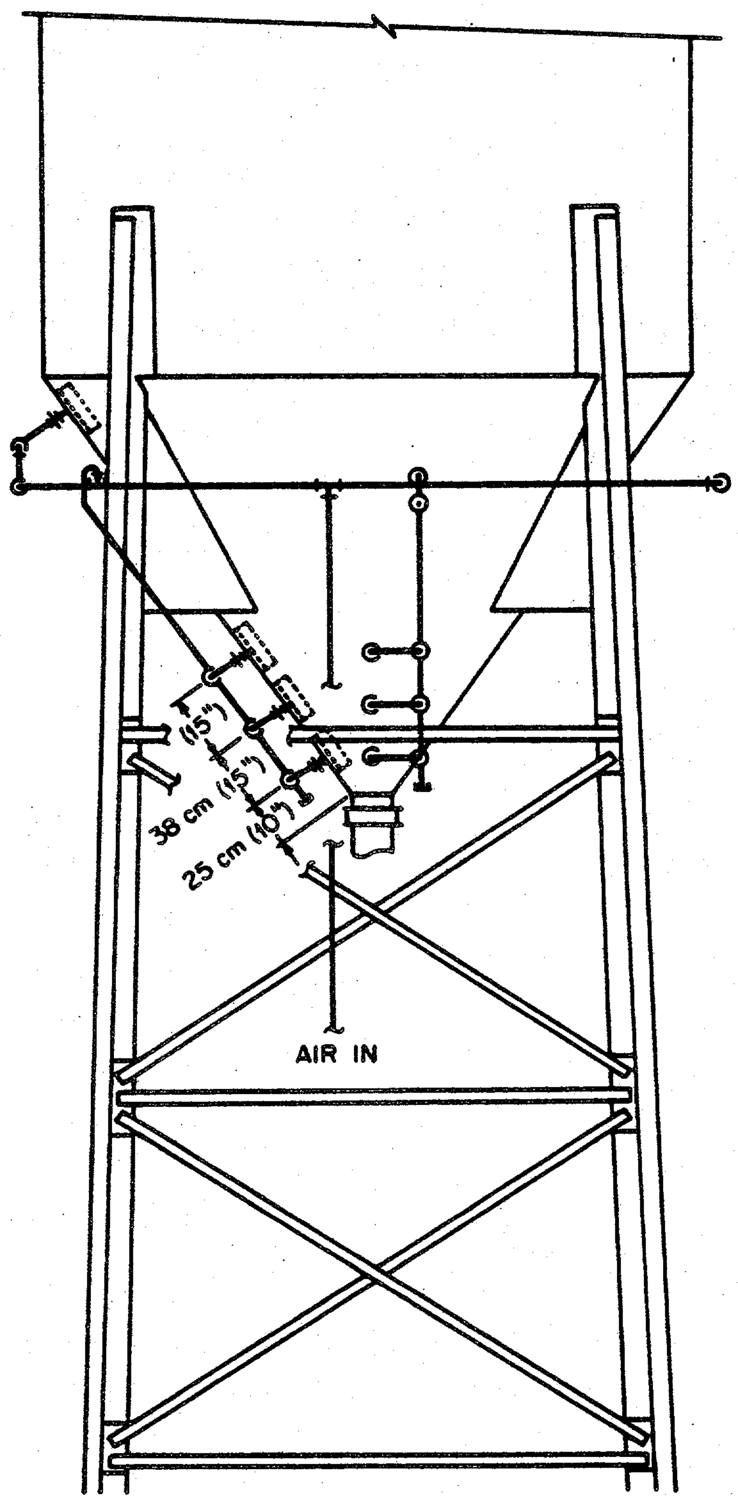

Fig. 21. Air-pad arrangement on bulk storage bin.

5.1.3 Preliminary maintenance

After the completion of ILW-16, the solids remaining in the bins were removed and disposed of. The bins were cleaned, and the mass meter was cleaned and reworked.

During the 4 days prior to Injection ILW-17, the valves in the high-pressure system were greased and worked. The cement was chipped out of one valve (V-9), and a 15-cm (6-in.) nipple was replaced. The core and inserts were changed on valves V-5 and V-14, and the relief valve was repaired. The injection pump was repacked, and new plungers were installed; all valves on the pump, two seats, and the pot gaskets were replaced.

Preliminary tests of the mass meter showed a consistent and grossly erroneous reading. Because the false reading could not be corrected prior to the injection, this instrument was not operated during the injection.

5.1.4 Slotting injection well

Pressurization of the injection well to break down the formation was unsuccessful. It seemed likely that the slot was plugged and that a new slot would have to be cut. Toward this end, the wellhead was rigged for slotting, and the tubing string was lowered to tag the bottom. The bottom was found to be at 246 m (807 ft) — approximately 15 m (5 ft) above the slot.

The well was slotted at 244 m (802 ft). The slotting pressure varied between 31 MPa (450 psi) at 570 ℓ/min (150 gpm) and 25 MPa (3500 psi) at 640 ℓ/min (170 gpm). Thirty-five sacks of sand and 22 kg (50 lb) of WG-6 suspender were used. The wellhead was rerigged for pumping, and the well was pressurized to break down the formation. Break-down occurred at 24 MPa (3500 psi) and 420 ℓ/min (110 gpm). The fracture was enlarged by gradually increasing the flow to 757 ℓ/min (200 gpm) at 25 MPa (3700 psi). A total of 2500 ℓ (660 gal) was pumped.

5.1.5 Solids blending

Five batches of dry solids were blended and loaded in the storage bins at the fracturing site. Four of these were loaded in the storage bins, while the remaining one was left in the blending tanks for later transfer to an empty bin. The plumb bob level indicator on bin 3 became stuck in a down position, and it was feared that if a full charge of solids were put in this bin, the indicator might break loose from its cord and plug the bin outlet, as had happened in Injection ILW-15. For this reason, only two P-tank loads of solids were charged to bin 3; the third P-tank load that would have normally been put into bin 3 was divided among bins 1, 2, and 4. As a consequence, the weight of solids charged to the individual bins was not precisely known for this injection. The weights of the various ingredients that were used for the solids mix are given in Table 13.

For Injection ILW-17, the solids contents of bins 1, 2, 3, and 4 were determined in the weigh tank and then transferred successively to a P-tank and a storage bin. This abbreviated blending procedure, which involved one fewer transfer than had been used in previous injections, resulted in an improvement in several respects.

The Portland cement was obtained from Ideal Basic Industries; the other mix components were obtained from the same suppliers as in Injection ILW-16.

5.2 Injection

The mass meter could not be made operable for this injection without a lengthy delay. Accordingly, the decision was made to monitor the proportioning of solids and waste by volume ratio calculations (as was done during the last half of Injection ILW-16). Here the volume ratio is the ratio of the volume of the injected grout (measured by the injection-pump stroke counter) to the volume of the waste solution (measured by the turbine flowmeter); this ratio is directly dependent on the proportion at which the waste solution and the dry solids are mixed. A plot of the correlation between these ratios is given in Fig. 13. The middle line of the correlation was used for the volume ratio calculations for this injection.

The volume ratio can be obtained by two methods, both of which were used in this injection. In one method, the volume of grout and the

Table 13. Dry solids mix for Injection ILW-17

Blending date	8/21/78	8/22/78	8/23/78	8/24/78	8/25/78
Bin number	4	3, 1	1, 2	2, 1, 4	P-tanks
Cement, kg (lb)	21,236 (46,720)	23,244 (51,243)	20,902 (46,080)	20,355 (44,875)	21,242 (46,830)
Fly ash, kg (lb)	23,329 (51,430)	24,513 (54,040)	26,490 (58,410)	23,512 (51,835)	20,380 (44,930)
Attapulgite, kg (lb)	8,414 (18,550)	8,754 (19,300)	8,405 (18,530)	8,333 (18,370)	8,587 (18,930)
Clay, kg (lb)	4,355 (9,600)	4,432 (9,770)	4,266 (9,405)	4,336 (9,560)	4,246 (9,360)
Sugar, kg (lb)	24 (54)	24 (54)	24 (54)	24 (54)	24 (54)
Total, kg (lb)	57,314 (126,354)	60,967 (134,407)	60,092 (132,479)	56,561 (124,694)	54,479 (120,104)

volume of waste pumped during a given time interval (usually 5 min) are noted from the stroke counter and integrated flowmeter readings. These readings are subtracted from previous readings, and the ratio of these differences is the average volume ratio for that particular time interval. The ratio indicator provides a second determination of the volume ratio. This device, first used in Injection ILW-16, takes signals from the stroke counter and the waste flowmeter and provides an indication of the volume ratio at that particular moment. This indication was zeroed during the preinjection slotting operation; it was recorded in Injection ILW-17.

Prior to the injection, the fracture was reopened and expanded by pumping water through the fracture. The fracture was reopened at a pressure of 41 MPa (6000 psi) and a flow rate of 454 ℓ/min (120 gpm). Approximately 3000 ℓ (800 gal) of water was pumped.

The injection was begun at 0832 on September 1, 1978, with water from the waste pit and solids from bin 3. The initial flow rates were kept low to minimize the injection pressure; after 15 to 20 min, the injection pressure had dropped sufficiently that the injection rate could be increased to about 606 ℓ/min (160 gpm) of waste [908 ℓ/min (240 gpm) of grout]. Plots of the injection pressure (wellhead measurement) and waste flow rate throughout the injection are shown in Figs. 22 and 23. The flow rate readings are average values (usually over a 5-min period) indicated by the turbine flowmeter.

During the injection, the volume ratio was calculated at 5-min intervals and the corresponding mix ratio was determined from the correlation shown in Fig 13. These values for the mix ratio are plotted in Fig 24. In Fig 25, the equivalent values from the recorded instantaneous volume ratio are given. These numbers are ~10% lower than those in Fig. 24 for the first 30 min of the injection, drastically lower for the next hour, and then almost identical for the remainder of the injection. No reason is known for the erratic performance of this instrument during the first 2 h of the injection.

The usual method for controlling the mix ratio (varying the solids feed rate to maintain an indicated mix ratio) could not be used in this injection because the mass meter was inoperable. Since the method of mix

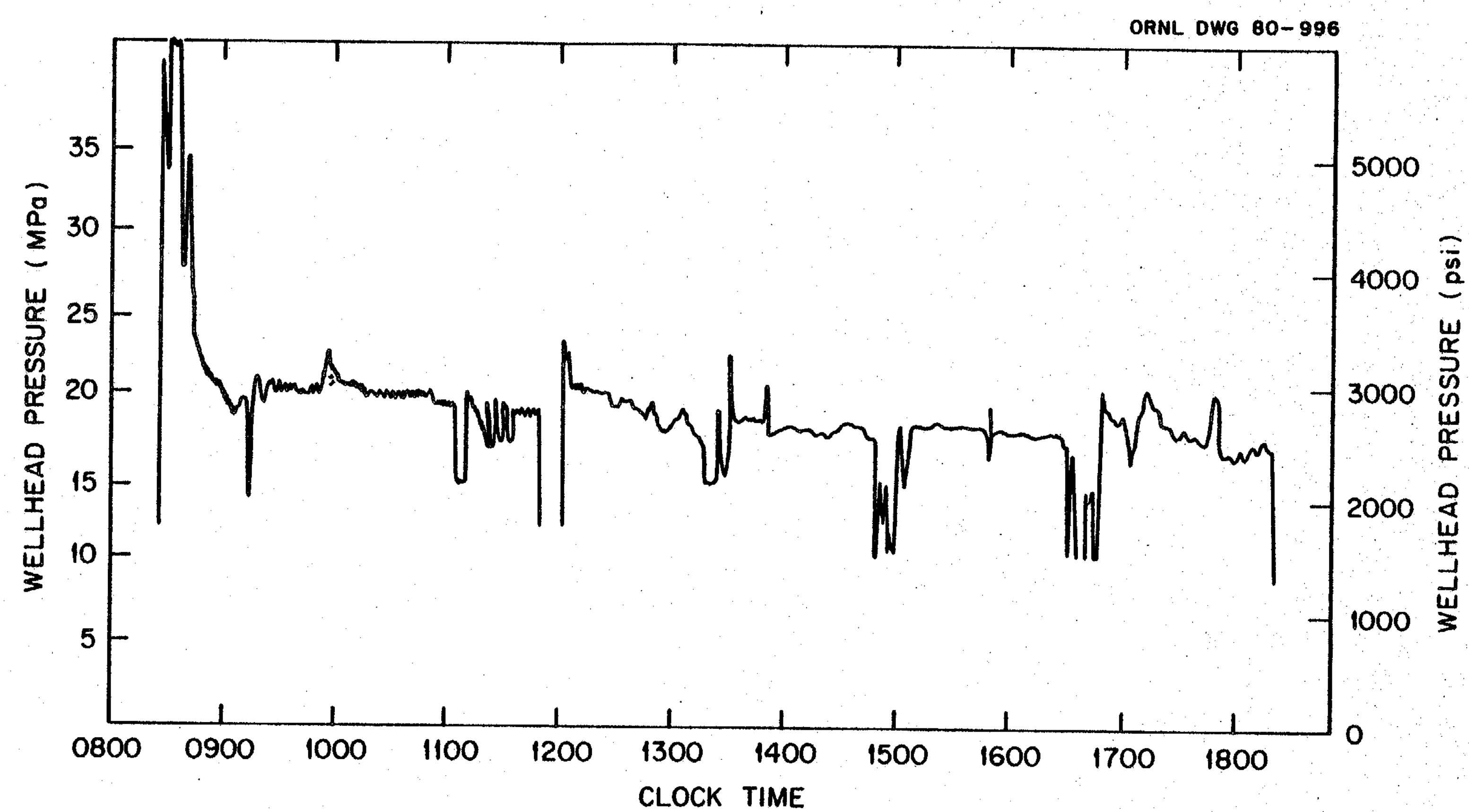

Fig. 22. Wellhead pressure measurements during Injection ILW-17.

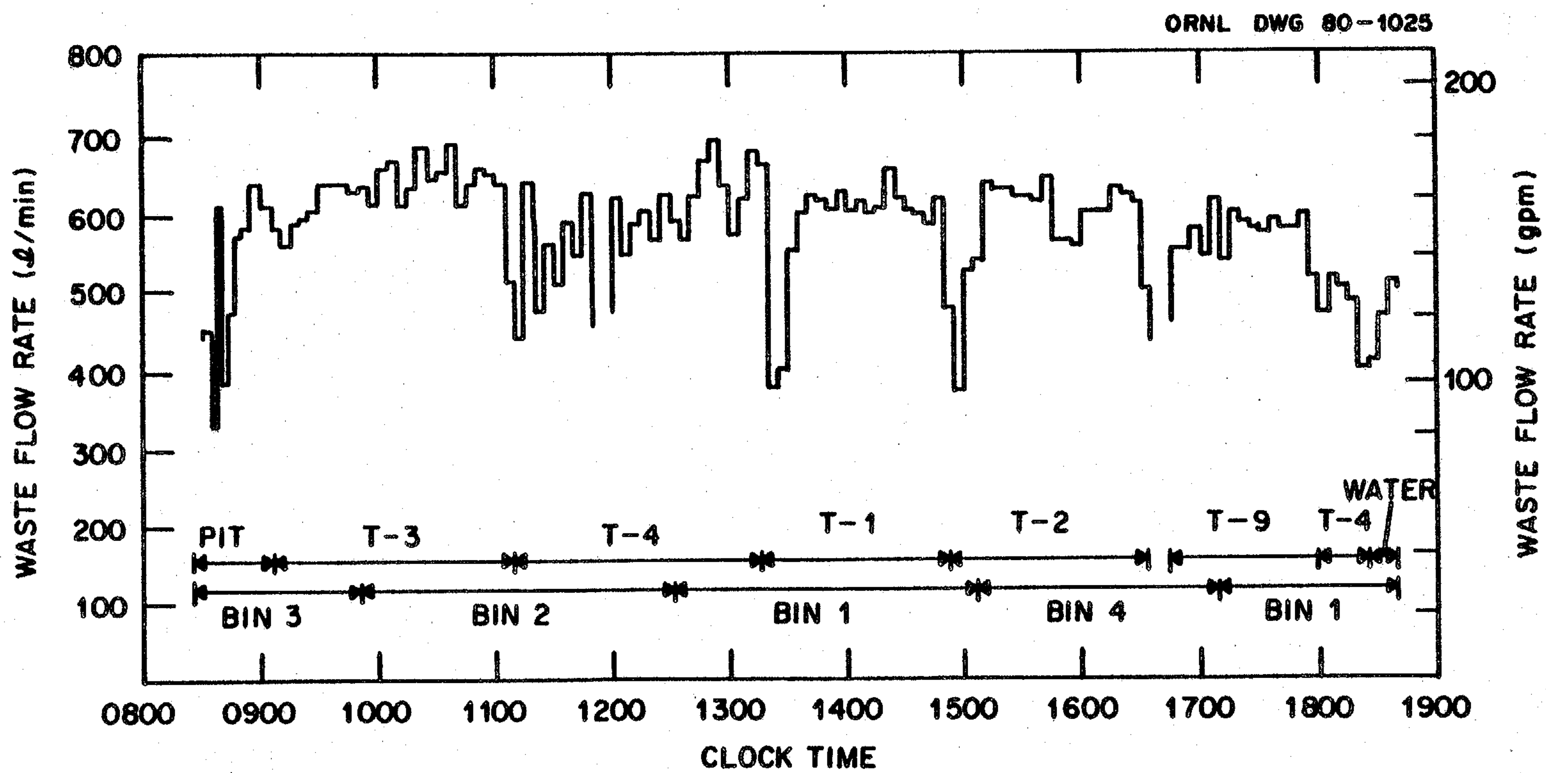

Fig. 23. Waste solution flow rates for Injection ILW-17.

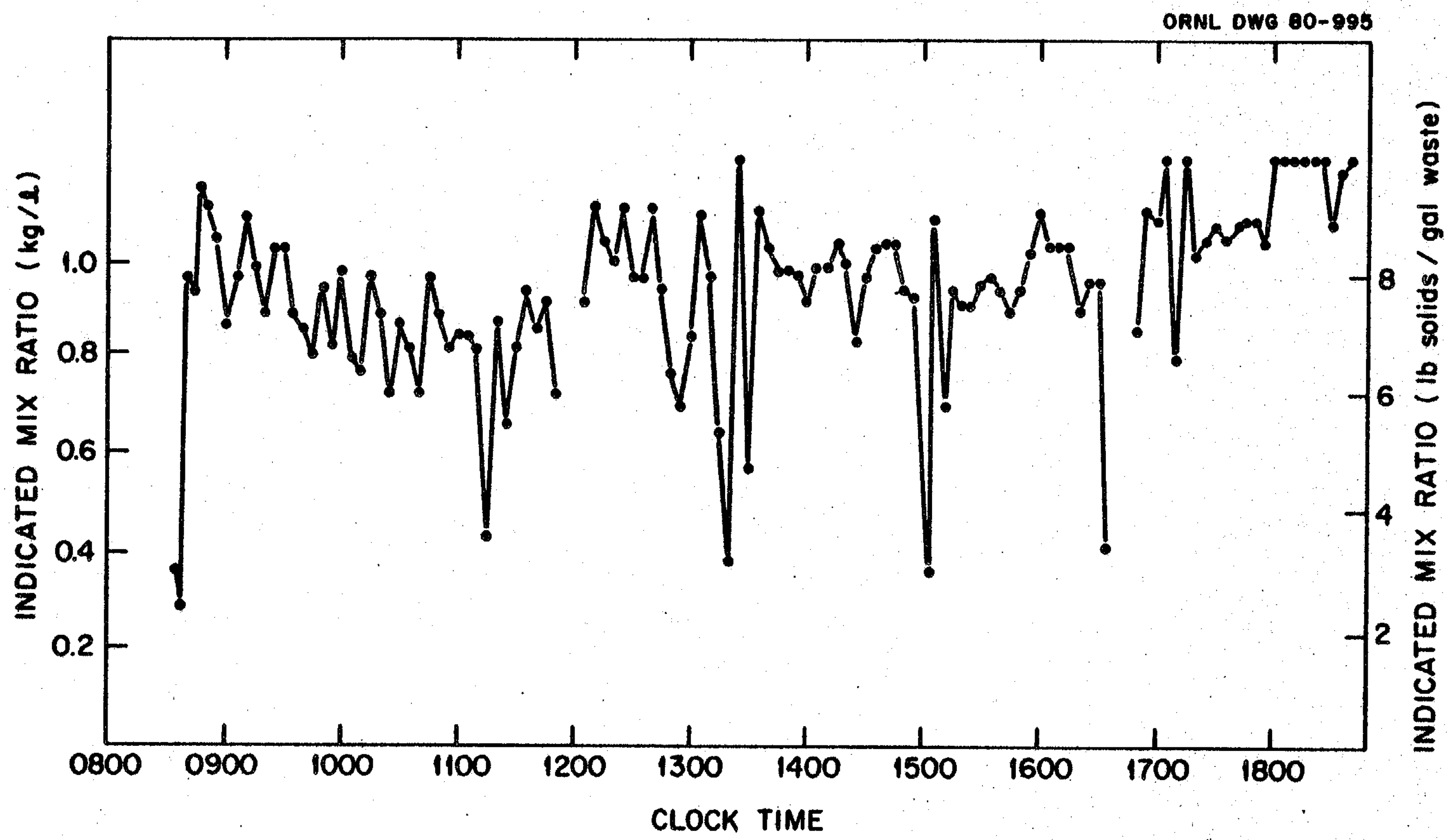

Fig. 24. Indicated mix ratios during Injection ILW-17.

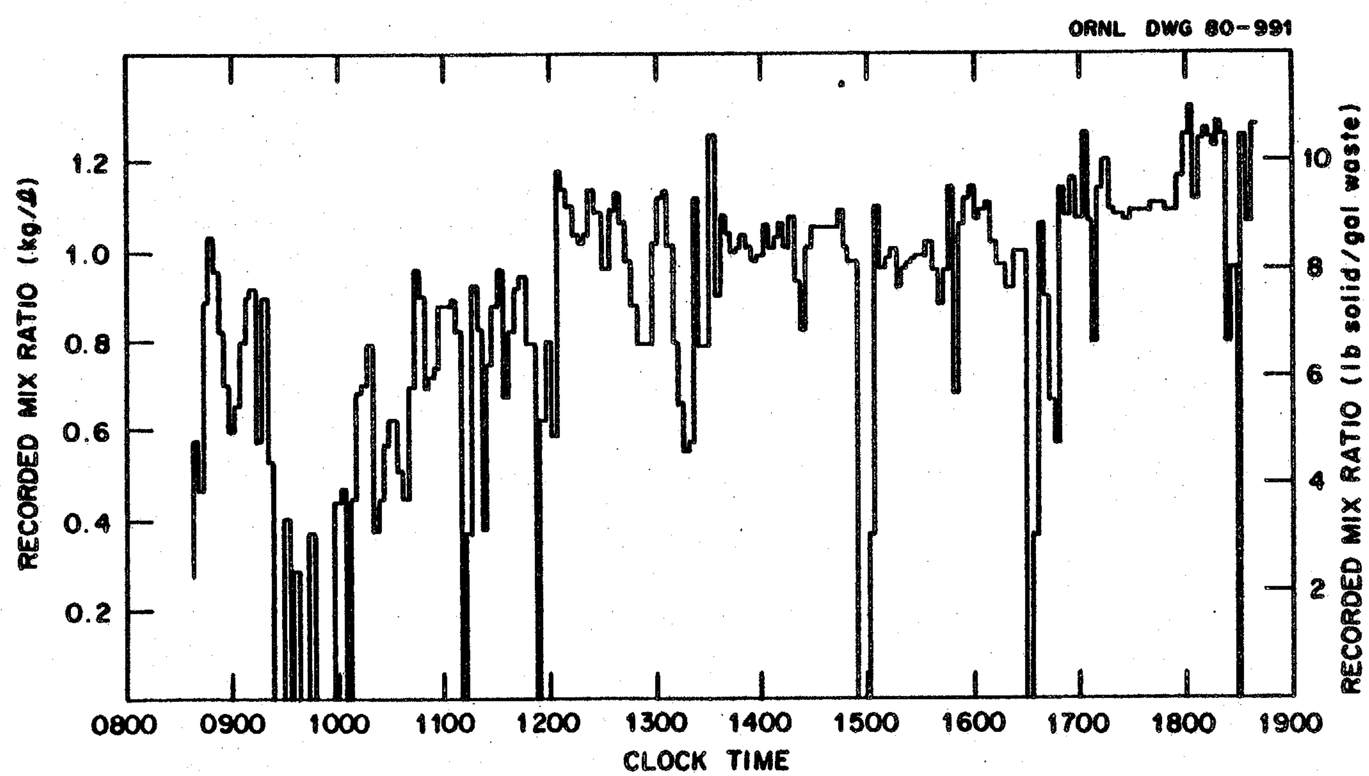

Fig. 25. Mix ratios during Injection ILW-17.

control used during the last half of Injection ILW-16 (occasional adjustment of the solids feed rate to correct the calculated mix ratio) had resulted in rather erratic control, a different operational technique was tried for this injection. After the injection conditions had stabilized, the solids flow valve was left in a fixed position and the mix ratio was controlled by bypassing waste solution around the mixing jet. If a different mix ratio was required, the volume of the bypass stream was reduced or increased, as needed, and no adjustment to the solids flow valve was made. This operating procedure was found to work exceptionally well; fluctuations in the mix ratio were smaller and less frequent than in previous injections and the corrections that had to be made were smaller and less frantic than those made heretofore.

In general, the flow of solids to the mixer in this injection was much improved over that in previous injections. Three factors were thought to be possibly significant: (1) the installation of the new air pads may have prevented the solids from sporadic bridging at the bin outlets, (2) the different operating technique (discussed in the previous paragraph) resulted in far fewer changes being made to the solids flow rate and gave this flow time to stabilize, and (3) solids that had been transferred twice during the blending operation (as was the case in this injection) had better flowability than those transferred three times (as was generally done in previous injections). The first of these factors is thought to have the major effect.

Twice during the injection — at 1113 and at 1634 — the window of the solids hopper had become completely obscured with dust and the injection was halted. The hopper was subsquently washed, and the injection was restarted.

As usual, some flow instabilities occurred whenever the waste pump suction was switched from one waste tank to another. At such times, the waste pump would lose its prime and several minutes would be required to reestablish normal flow. Except for these irregularities, the injection proceeded quite smoothly.

During the run, a running total was kept of the calculated consumption of dry solids. By about 1200, it was clear that the calculated consumption was higher than the actual consumption by ∿15%; thus the mix ratio was increased to ~0.96 kg/ℓ (8 lb/gal) to compensate for the discrepancy. By 1500, when bin 1 ran empty, another check was possible. Because the results indicated that a difference between calculated and actual consumption still existed, the mix ratio was increased again — to between 1.08 kg/ℓ (9 lb/gal) and 1.2 kg/ℓ (10 lb/gal). These high apparent ratios were maintained until the the injection had been completed.

At 1826, the waste tanks were essentially empty and flow was switched to fresh water. The solids flow was stopped at 1834, and the injection was ended at 1840.

The wiper plug was pumped down the well with 3180 ℓ (840 gal) of water. Another 2380 ℓ (630 gal) was pumped down the casing annulus. Then the well was valved shut, and the equipment was washed. During the washdown operation, one of the hoses between the sump tub and the suction manifold of the HT-400 was found to be plugged with sand.

Readings of the pressures in the rock cover wells (Table 14) were taken at intervals during the injection. These pressure changes are smaller than those usually observed.

5.3 Data Analysis

The volume of waste solution or pit water pumped during this injection was measured by three methods. The solution flow to the mixer was measured by a turbine flowmeter as well as a recording orifice meter. The volume of waste solution pumped was measured by the change in tank solution level. The agreement between the tank level measurements and the turbine flowmeter readings was very good; the orifice meter readings were ~9% low. For the time interval during which waste was being pumped from the storage tanks (between 0906 and 1752), for instance, the tank level measurements indicated that 292,150 ℓ (77,186 gal) of waste were pumped, the turbine flowmeter indicated 294,610 ℓ (77,837 gal), and the orifice meter indicated 268,800 ℓ (71,018 gal). The turbine meter readings are generally more convenient to use than the tank level readings or the orifice meter readings; therefore, they are used in the subsequent calculations.

Table 14. Pressure readings, in kPa (psig), of rock cover wells during Injection ILW-17

Rock cover well	Reading taken on September 1, 1978, at:				
	0920	1240	1440	1540	1720
E-300	148 (21.5)	210 (30.5)	238 (34.5)	241 (35)	252 (36.5)
NE-125	0	0	-17.2 (-2.5)	-24.1 (-3.5)	-32.4 (-4.7)
NE-200	-37.2 (-5.4)	-64.1 (-9.3)	-73.1 (-10.6)	-77.9 (-11.3)	-81.4 (-11.8)
N-200	-40.7 (-5.9)	-67.6 (-9.8)	-71.0 (-10.3)	-74.5 (-10.8)	-84.8 (-12.3)
N-275	31.0 (4.5)	20.7 (3)	3.4 (0.5)	0	-4.8 (-0.7)
NW-175	-20.0 (-2.9)	-47.6 (-6.9)	-57.2 (-8.3)	-60.7 (-8.8)	-69.6 (-10.1)
NW-250	34.5 (5)	20.7 (3)	3.4 (0.5)	0	-6.9 (-1.0)
W-300	-3.4 (-0.5)	-3.4 (-0.5)	0	-3.4 (-0.5)	0
S-200	137.9 (20)	141.3 (20.5)	137.9 (20)	134.5 (19.5)	131.0 (19)

The volumes of grout injected were measured by the stroke counter on the injection pump. These volumes were recorded at 5-min intervals.

Weights (strain gages) on bins 1, 3, and 4 were noted at intervals. Bin 2 has no usable weigh gage installed. The bin level measurements (plumb bobs) were not used in this injection because of a fear that the float part of the unit might be broken from the unit, as had occurred in an earlier injection.

The readings obtained with the strain gage on bin 3 were not credible since they indicated that the amount of solids withdrawn was 26% of the amount determined via the mix ratio calculations. The strain gages on bins 1 and 4 indicated that the amount of solids withdrawn was between 77 and 92% of that suggested by the mix ratio calculations. The latter numbers are not unreasonable since the mix ratio calculations indicated that more solids were being consumed than were originally stored in the bins. The strain gage measurements generally showed a uniform withdrawal rate of solids; Fig. 26 shows the calculated amount of solids withdrawn from bin 4 based on strain gage measurements and on mix ratio calculations.

The bulk storage bins contained an appreciable amount of solids at the end of the injection. Twenty truck loads of solids were removed from the four storage bins: six loads from bin 1, six from bin 4, four from bin 2, and four from bin 3. Each truck load is estimated to contain ∿1000 kg (2200 lb) of solids. The weight of solids charged to bin 3 was 40,610 kg (89,530 lb), and the weight of solids charged to the P-tanks was 55,256 kg (121,817 lb). The weight of solids charged to each of the other three bins is somewhat uncertain because one 18,100-kg (40,000-lb) batch of solids was divided among the three bins and the precise quantity of solids charged to each bin could not be determined. It is estimated, however, that bin 1 contained 66,680 kg (147,000 lb) of solids, bin 2 contained 64,000 kg (141,000 lb), and bin 4 contained 63,500 kg (140,000 lb). One needs only to subtract the amount of solids remaining at the end of the injection from these numbers in order to obtain the approximate weight of solids consumed. These numbers, given in Table 15, are compared with the calculated solids consumption based on the volumetric ratio readings and the correlation

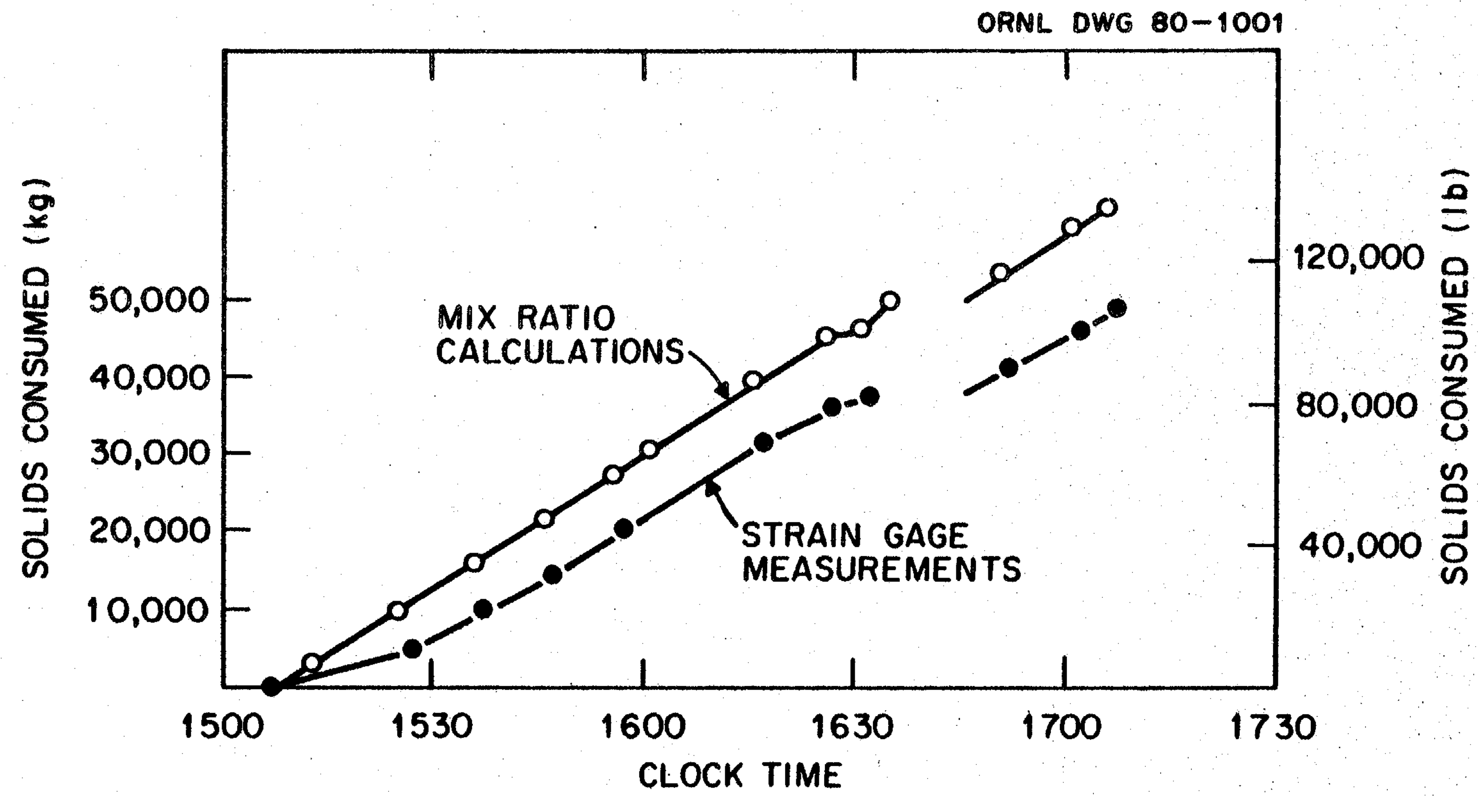

Fig. 26. Two measurements of solids withdrawn from bin 4 during Injection ILW-17.

Table 15. Comparison of mix ratios for Injection ILW-17

Time	Bin	Actual solids use (kg)	Actual solids use (lb)	Waste volume (ℓ)	Waste volume (gal)	Actual mix ratio (kg/ℓ)	Actual mix ratio (lb/gal)	Calculated solids use (kg)	Calculated solids use (lb)	Calculated mix ratio (kg/ℓ)	Calculated mix ratio (lb/gal)	Actual / calculated
0832-0952	3	36,680	80,700	45,800	12,100	0.80	6.67	41,550	91,600	0.91	7.57	0.88
0952-1232	2	60,100	132,200	92,090	24,330	0.65	5.43	78,650	173,400	0.86	7.13	0.76
1232-1507	1	64,500	142,000	89,590	23,670	0.72	6.00	78,830	173,780	0.88	7.34	0.82
1507-1708	4	57,600	126,800	67,300	17,780	0.86	7.13	63,890	140,850	0.95	7.92	0.90
1708-1834	1	51,600	113,600	48,370	12,780	1.07	8.89	55,260	121,817	1.14	9.53	0.93

given in Fig. 12. It seems apparent from the data in Table 15 that the calculated mix ratio was 10 to 20% higher than the actual mix ratio. This error can be compensated for in future injections by an alteration of the calibration curve (Fig. 12).

5.4 Evaluation of the Injection

The most distinguishing feature of Injection ILW-17 was the smoothness of operation. The solids flowed evenly from the bulk storage bins without the stops, starts, and slug flow characteristic of solids flow during previous injections. Also, the control of the solids to liquid mixing was devoid of the 30-min cycles that were so apparent during the last half of Injection ILW-16. This improvement was largely the result of a different operator technique, but was assisted by the more uniform solids flow.

Some irregular operation occurred immediately before and after the suction of the waste pump was switched from one waste tank to another. The waste pump loses its prime, and a period of several minutes is required before normal operation can be resumed. This problem appears to be characteristic of the design of the waste piping system and probably cannot be easily corrected.

Periodic cleaning of the mixer hopper is still required, sometimes because vision into the hopper gradually becomes obscured and on other occasions because solids accumulate in the hopper and interfere with normal flow. No simple correction for such situations can be suggested.

All instrumentation (except for the mass meter) worked well. Even the strain gages on two of the solids storage bins gave reliable readings.

5.5 Post-Injection Operations

The pressure in the annulus of the injection well was observed at intervals after the injection. The final injection pressure, which was 186 MPa (2700 psi), fell to ~6.9 MPa (1000 psi) approximately 30 min after the end of the injection and declined slowly thereafter. The rate of pressure decay was lower than after Injection ILW-16 but about the same as after Injection ILW-15.

Following the injection, all the cased observation wells that were serviceable were logged. Well NE-125, whose casing had been pulled apart during Injection ILW-13, is badly contaminated and no longer usable. The casing of well W-300 was ruptured during Injection ILW-14. No grout sheet that could be attributed to injection ILW-17 was observed in well E-300, N-100, or NW-100. A new peak was observed in well S-220 at 240 m (787 ft); in addition, a possible peak was observed in well N-150 at 252 m (826 ft). The log is somewhat ambiguous, however, and the latter peak may simply be higher resolution of an existing peak.

A bleedback of free water from injection ILW-17 was attempted. No water was collected.

The rock cover monitoring wells were tested to determine the rate of water acceptance. Each well was pressurized to 517 kPa (75 psi) with a gas cylinder, and the volumes of water accepted after 1 and 2 h were determined. With the exception of well W-300, the results obtained were quite similar to those obtained on previous occasions, indicating that the integrity of the overlying rock formation has not changed. (In the case of W-300, a leak at the coupling precluded any meaningful data.) The results are given in Table 16.

Table 16. Water acceptance rates for rock cover monitoring wells, in ℓ/h (gph)

Rock cover well	1979		1973	
	First hour	Second hour	First hour	Second hour
NW-175	8.5 (2.25)	8.2 (2.17)	5.7 (1.5)	5.7 (1.5)
NW-250	0.89 (0.24)	1.0 (0.26)	1.1 (0.3)	1.1 (0.3)
W-300	3.05 (0.81)	5.54 (1.46)	0.4 (0.1)	None
S-300	1.64 (0.43)	1.28 (0.34)	2.8 (0.75)	1.9 (0.5)
E-300	0.12 (0.032)	0.10 (0.026)	None	None
N-275	0.25 (0.066)	0.19 (0.050)	0.2 (0.05)	0.2 (0.05)
NE-125	5.38 (1.42)	3.33 (0.88)	4.5 (1.2)	4.5 (1.2)
N-200	2.73 (0.72)	2.00 (0.53)	4.5 (1.2)	4.5 (1.2)
NE-200	2.03 (0.54).	1.64 (0.43)	1.9 (0.5)	1.9 (0.5)

6. INJECTION ILW-18

6.1 Preliminary Preparations

6.1.1 Waste transfer and analysis

The waste solutions available for Injection ILW-18 consisted of 113,600 ℓ (30,000 gal) of waste in tank W-8, 151,400 ℓ (40,000 gal) of waste in tank W-10, and ∿37,800 ℓ (10,000 gal) of waste in other tanks. Samples were taken of the solutions in tanks W-8 and W-10 and analyses were obtained (Table 17). The remaining waste solutions were not sampled or analyzed; their operational history indicated that they were quite dilute as compared with the solutions in W-8 and W-10, would contain few radionuclides, and would behave chemically like slightly impure water.

The waste solution from tank W-8 was stored in tanks T-1 [55,910 ℓ (14,772 gal)] and T-2 [18,900 ℓ (5,000 gal)]. The waste solution from tank W-10 was pumped to tanks T-2 [37,460 ℓ (9,897 gal)], T-4 [93,520 ℓ (24,709 gal)], T-9 [49,100 ℓ (12,975 gal)], and T-3 [53,000 ℓ (14,000 gal)]. The remaining space in Tank T-3 was filled with dilute miscellaneous waste [39,580 ℓ (10,458 gal)].

6.1.2 Solids blending

Five batches of dry solids were blended and loaded in the storage bins at the fracturing site. Four of them were loaded in the storage bins, while the fifth was left in the blending tanks for later transfer to an empty bin. The abbreviated blending procedure used in the preparations for Injection ILW-17 was followed in the preparation of the first four batches; the dry solids were loaded in the scale tank, and were then blown sucessively to the first blending tank and to the storage bin. The second blending tank was not used; however, since the storage capacity of the second blending tank was needed for storage of the final batch of solids, this batch of solids was blended an additional time. The weights of the various ingredients that were used for the solids mix are given in Table 18.

Table 17. Analyses of waste solutions for Injection ILW-18

	Tank W-8	Tank W-10
Volume, ℓ (gal)	114,000 (30,000)	150,000 (40,000)
Specific gravity	1.2018	1.1186
Al^{3+}, M	0.041	0.03
Cu^{2+}, M	1.5×10^{-3}	1.1×10^{-3}
K^{+}, M	0.389	0.136
Na^{+}, M	3.37	1.88
OH^{-}, M	0.64	0.29
$CO_3{}^{2-}$, M	0.50	0.27
$SO_3{}^{2-}$, M	0.04	0.045
$NO_3{}^{-}$, M	1.6	0.968
Gross α, Ci/ℓ (Ci/gal)	3.7×10^{-6} (1.4×10^{-5})	2.6×10^{-6} (9.7×10^{-6})
Gross γ, Ci/ℓ (Ci/gal)	8.6×10^{-3} (3.3×10^{-2})	1.1×10^{-2} (4.2×10^{-2})
^{137}Cs	0.063 (0.239)	4.4×10^{-2} (0.165)
^{134}Cs	3.0×10^{-4} (1.1×10^{-3})	2.1×10^{-3} (8.0×10^{-3})
^{90}Sr	1.0×10^{-4} (4.0×10^{-4})	1.0×10^{-4} (4.0×10^{-4})
^{60}Co	5.0×10^{-4} (2.1×10^{-3})	5.0×10^{-4} (2.0×10^{-3})
Cm	1.53×10^{-6} (5.8×10^{-6})	1.24×10^{-7} (4.7×10^{-7})
Pu	3.17×10^{-7} (1.2×10^{-6})	1.67×10^{-6} (6.3×10^{-6})

Table 18. Dry solids mix for Injection ILW-18

	Bin 1	Bin 2	Bin 3	Bin 4	P-tanks
Blending date	5/11/79	5/10/79	5/9/79	5/8/79	5/14/79
Cement, kg (lb)	21,452 (47,194)	21,755 (47,860)	21,255 (46,760)	21,114 (46,450)	21,355 (46,980)
Fly ash, kg (lb)	26,355 (57,980)	22,600 (49,720)	24,936 (54,860)	26,127 (57,480)	26,332 (57,930)
Attapulgite, kg (lb)	8,700 (19,140)	8,732 (19,210)	8,505 (18,710)	8,455 (18,600)	7,885 (17,348)
Pottery clay, kg (lb)	4,400 (9,680)	4,459 (9,810)	4,373 (9,620)	4,510 (9,922)	4,345 (9,560)
Sugar, kg (lb)	25 (54)	25 (54)	25 (54)	25 (54)	25 (54)
Total, kg (lb)	60,931 (134,048)	57,570 (126,654)	59,093 (130,004)	60,271 (132,596)	59,942 (131,872)

A new solids feeder was used to replace the Halliburton screw conveyer that charged attapulgite and pottery clay to the scale tank. This feeder was a Carter-Day "Air Swept" feeder valve, which utilized a flow of air through a rotary valve to aerate and transfer the solids being fed through the valve. As installed, the operation was found to be too dusty; therefore, the valve was removed and the screw conveyer reinstalled.

6.1.3 Tests of mix compatibility

The blended dry solids from each of the storage bins were sampled and tested with synthetic waste solutions. A few tests were also made with water. Phase separation and rheological properties were determined for grouts made with various mix ratios. Most of the tests were made with grouts that were prepared by mixing the dry solids and waste solution at both 5000 rpm (to simulate down-hole conditions) and 2000 rpm (to simulate tub conditions). The results of a selection of the mix compatibility tests are shown in Table 19. As usual, some differences were observed between the characteristics of the grouts sheared at 2000 rpm and those sheared at 5000 rpm. The additional shear approximately doubled the apparent viscosity of the grout and reduced its phase separation by several percent. These differences, which are similar to those observed heretofore, were expected. However, the high apparent viscosities and low phase separations that were observed at very low mix ratios were not entirely expected. The characteristics of these grouts at mix ratios of 0.48 and 0.6 kg/ℓ (4 and 5 lb/gal) were approximately equivalent to those determined for Injection ILW-16 at 0.84 and 0.96 kg/ℓ (7 and 8 lb/gal). Part of this difference may be due to the more concentrated waste solution that was disposed of in Injection ILW-18; on the other hand, since the compatibility tests with water showed much the same effects, the major part of the difference could probably be attributed to the abbreviated blending procedure used for the solids in this injection. Although this phenomenon has been observed previously, the magnitude of the difference in this case was somewhat larger than anticipated.

The results of these tests indicated that a mix ratio of about 0.72 kg/ℓ (6 lb/gal) would generally produce a grout with a low phase

Table 19. Mix compatibility tests for Injection ILW-18[a]
(All tests made at 5000 rpm)

Bin number	Solution	Mix ratio (kg/ℓ)	Mix ratio (lb/gal)	Density (kg/ℓ)	Density (lb/gal)	Phase separation (%)	Apparent viscosity (cP)
4	W-10	0.60	5	1.333	11.1	4	14.0
		0.72	6	1.381	11.5	1.4	24.5
	Water	0.72	6	1.309	10.9	4.1	24
		0.84	7	1.345	11.2	2.8	35
3	W-8	0.60	5	1.375	11.45	0.9	12.5
		0.72	6	1.405	11.7	0.6	21
		0.84	7	1.429	11.9	0	41
2	W-10	0.36	3	1.245	10.4	1.8	10
		0.48	4	1.279	10.65	0	30
	W-8	0.60	5	1.363	11.35	0.2	19.5
		0.72	6	1.387	11.55	0	42
	Water	0.72	6	1.285	10.7	3.6	21
		0.84	7	1.339	11.15	1.7	32.5
1	W-8	0.60	5	1.345	11.2	3	25.5
	W-10	0.60	5	1.309	10.9	2.1	16
		0.72	6	1.345	11.2	1.6	33
	Water	0.48	4	1.201	10.0	1.9	28
		0.72	6	1.321	11	0	52

[a]Data from J. G. Moore.

separation and an apparent viscosity of ~30 cP. However, the particular combination of bin 2 solids and W-10 waste seemed to require a lower mix ratio. A mix ratio of about 0.48 kg/ℓ (4 lb/gal) appeared to be the upper limit for this combination; at higher mix ratios, the viscosity of the grout appeared to be excessive.

6.1.4 Slotting injection well

The injection well was pressurized to break down the formation, but no breakdown occurred. Circulation down the tubing string and up the annulus was attempted but not achieved. The tubing string was disconnected from the wellhead assembly and lifted to verify that it was not cemented to the well bottom. Circulation down the tubing string was attempted while the tubing was held off the well bottom, but the attempt was not successful. When the tubing string was logged, a plug was found at ~12 m (40 ft) above the bottom of the string.

The tubing string was removed from the well. The lower two joints — one 1.8 m (6 ft) long, and one 9 m (30 ft) long — were found to be plugged with cement interspersed with pockets of water. The rubber-wiper plug was located ~1.5 m (5 ft) from the bottom of the tubing string. The plugged joints were replaced, and the tubing string was reinserted in the well. The string was then lowered to touch bottom, which was found to be 1.5 m (5 ft) above the slot of the previous injection.

The well was slotted at 244 m (784 ft). The slotting pressure varied between 32 MPa (4600 psi) at 606 ℓ/min (160 gpm) and 20 MPa (2950 psi) at 795 ℓ/min (210 gpm); 50 sacks of sand and 22 kg (50 lb) of WG-6 suspender were used. The wellhead was rerigged for pumping, and the well was pressurized to break down the formation. Breakdown occurred at 23 MPa (3400 psi) and 636 ℓ/min (168 gpm).

6.1.5 Miscellaneous maintenance

Several maintenance procedures were necessary prior to the injection. For example, the mass meter, which had become inoperable, was removed and reworked. Inspection revealed that cement had gotten inside the mechanism and caused it to malfunction. The instrument was cleaned, calibrated, and reinstalled.

The plungers and packing of the injection pump were replaced (on conclusion of the slotting operation). The packing was then run in.

All valves were pressure tested and the relief valve was set at 36 MPa (5200 psi). The check valve, the master valve, and valve V-9 were repaired.

The injection pump would not shift properly. Examination revealed a rusted air cylinder, which was subsequently replaced.

6.2 Injection

Mix compatibility tests had indicated that the grout viscosity might be appreciably higher than usual in this injection, particularly with certain combinations of waste solutions and solids mixes. Therefore, the sequence of waste tank drawdown and bin usage was planned to avoid those combinations that tests had indicated would be most difficult to pump.

The mix ratio for this injection was automatically computed from mass-meter and turbine flowmeter readings and recorded. The mix ratio was also determined from the ratio of the pumped volumes of grout and waste solution, measured by the stroke counter of the injection pump and the turbine flowmeter. This ratio was also recorded. This ratio was converted to a mix ratio by the correlation shown in Fig. 13. During Injection ILW-18, both of the mix ratio determinations were used. The mix ratio was calculated at approximately 5-min intervals from both the mass-meter readings and the volume ratio measurements. The two values thus obtained were then compared to determine whether a consistent bias existed in either set of readings.

Prior to the injection, the fracture was reopened and expanded by pumping water through the fracture. The fracture was reopened at a pressure of 34 MPa (4900 psi) and a flow rate of 454 ℓ/min (120 gpm). Approximately 4000 ℓ (1050 gal) of water was pumped.

The injection was begun at 0840 on May 18, 1979, with water from the waste pit. Solids flow was started from bin 2 at 0844. At 0912, the waste pit was nearly empty and flow was switched to T-1. Plots of the injection pressure (wellhead measurement) and waste flow rate throughout the injection are shown in Figs. 27 and 28. The flow rate readings are average values (usually over a 5-min period) indicated by the turbine flowmeter.

The indicated mix ratio as determined from the volume ratio is shown in Fig. 29. A comparison of the mix ratio calculated from mass-meter readings with the mix ratio calculated from volume ratio readings is shown in Fig. 30. The mix ratios calculated by the two different methods are in very good agreement except for the last 30 min of the injection. This discrepancy is discussed later.

At 1008, the injection was halted due to a leak in the mixing cell, and the source of the leak was determined. Examination revealed a hole in the discharge line from the mixing jet (probably eroded during the slotting operation). About 3400 ℓ (900 gal) of waste was pumped to dilute the grout in the mixing tub and high-pressure lines. A piping patch, which was obtained and strapped to the leaking line, stopped the leak and permitted continuation of the injection.

During the shutdown period (when there was no solids flow), the mass meter was observed to be indicating a positive solids flow of 190 kg/min (420 lb/min). It seemed apparent that some solids buildup had occurred on the sensing cone of the mass meter and was biasing the readings. The magnitude of this bias appeared to be ∿10% (during the previous 30 min of operation, the mass-meter readings had averaged 10% higher than the volume ratio measurements), and the zero of the mass meter was adjusted accordingly.

The injection was resumed at 1127 and continued without incident until 1620. During this period, the flow of solids to the mixer was smooth (as had been the case in Injection ILW-17), and fluctuations in the mix ratio were smaller and less frequent than in most previous injections. The mix ratio indicated by the mass-meter readings was in good agreement with that calculated from the volume ratio measurements, although a running inventory of the weight of solids withdrawn from a storage bin gave a somewhat greater weight than had originally been charged to the bin. The viscosity of the grout mix did not appear to be excessive, even at mix ratios appreciably higher than those that had resulted in very thick grouts in the mix compatibility tests.

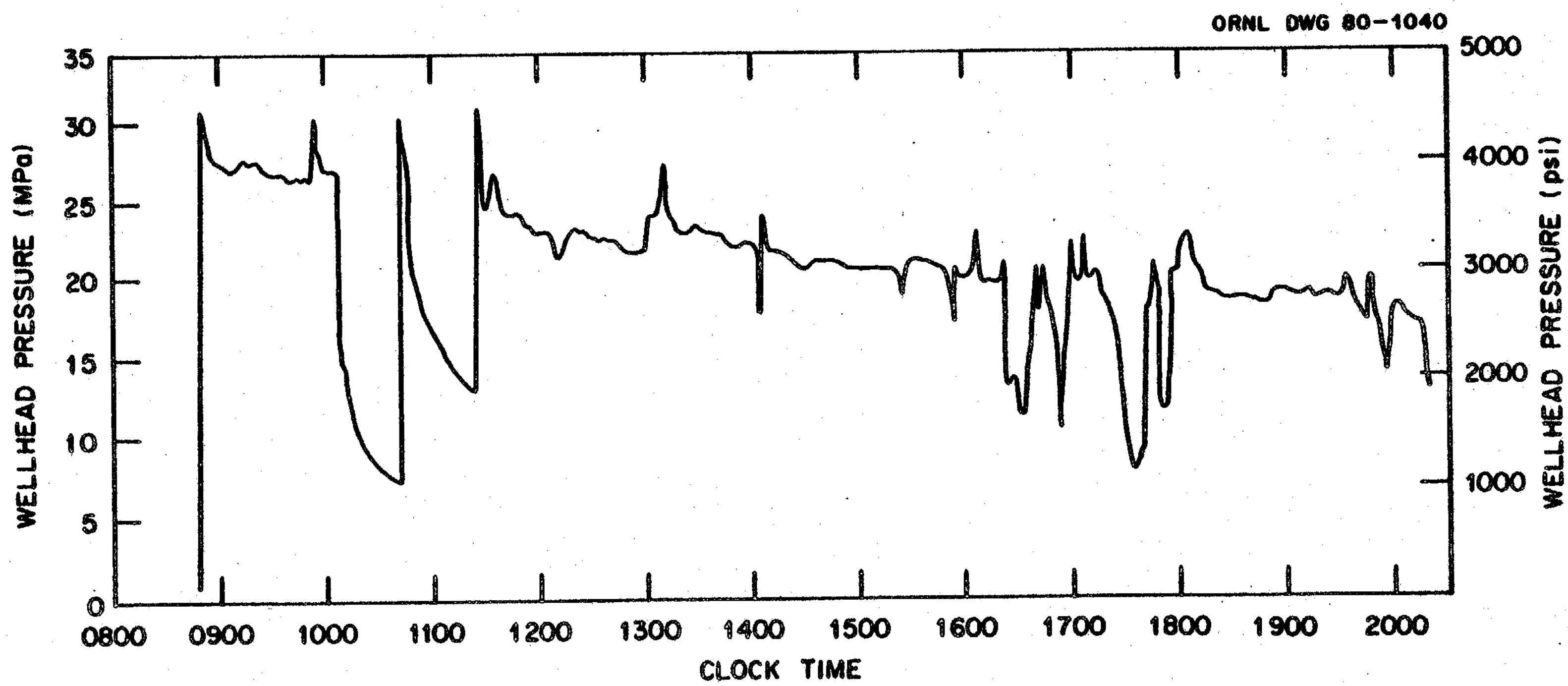

Fig. 27. Wellhead pressure measurements during Injection ILW-18.

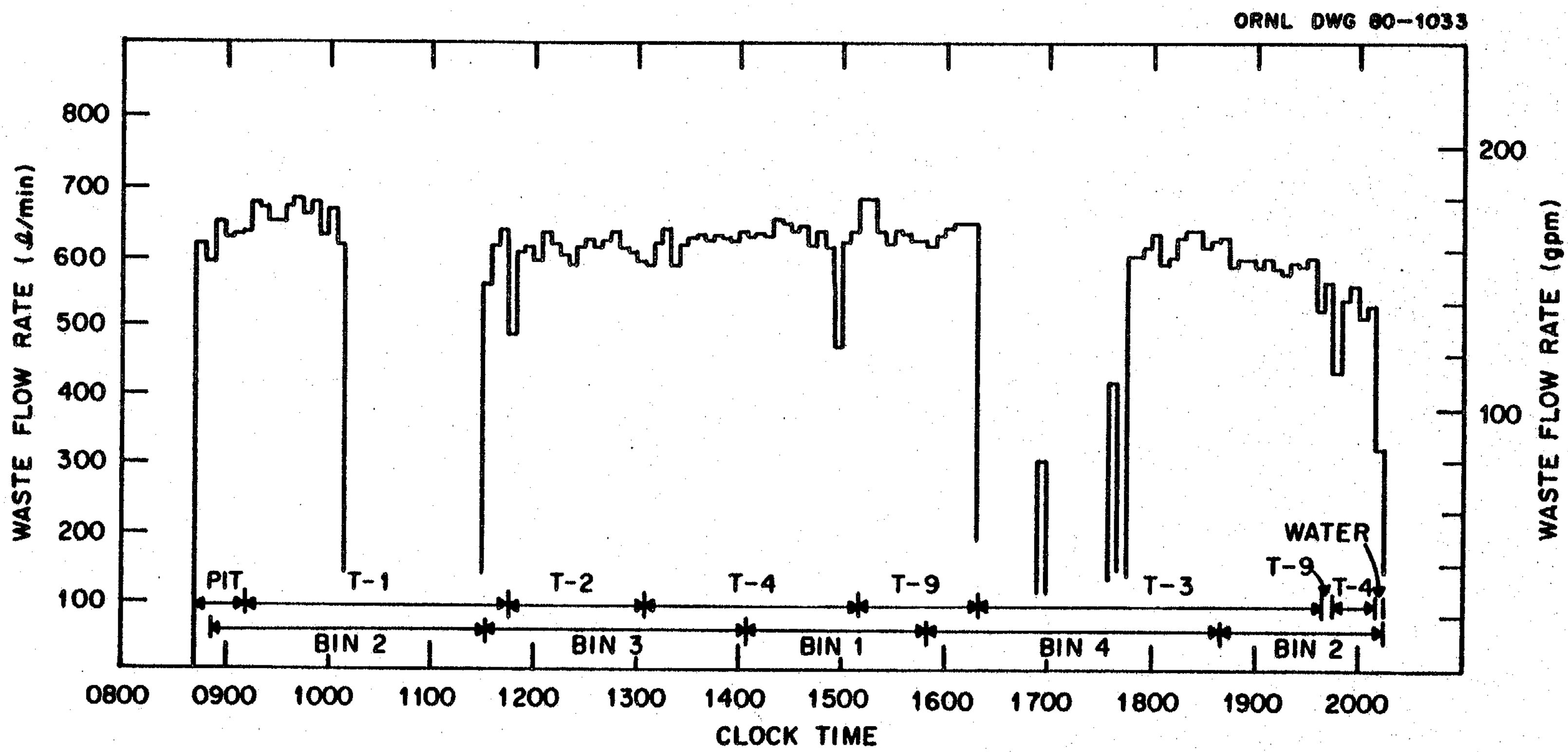

Fig. 28. Waste solution flow rates during Injection ILW-18.

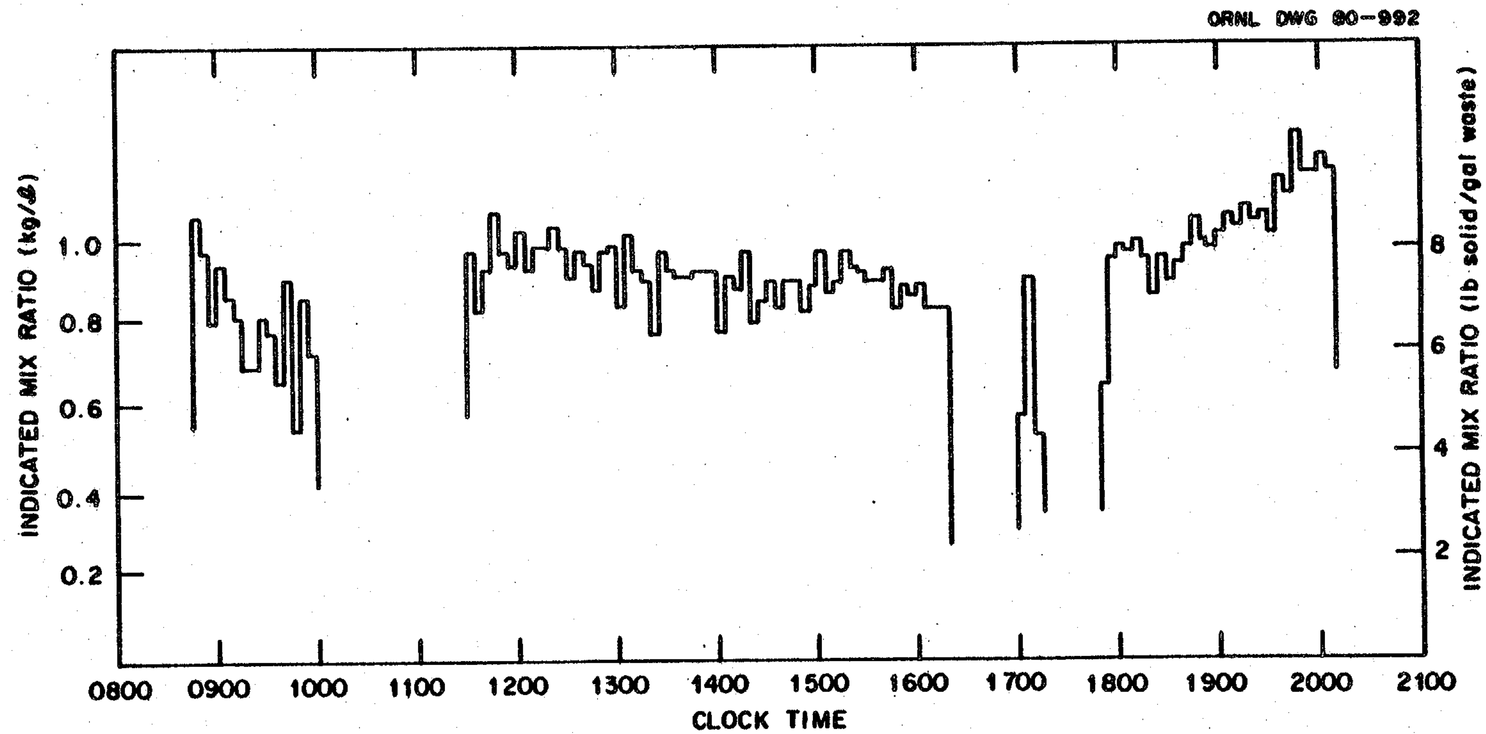

Fig. 29. Indicated mix ratios for Injection ILW-18.

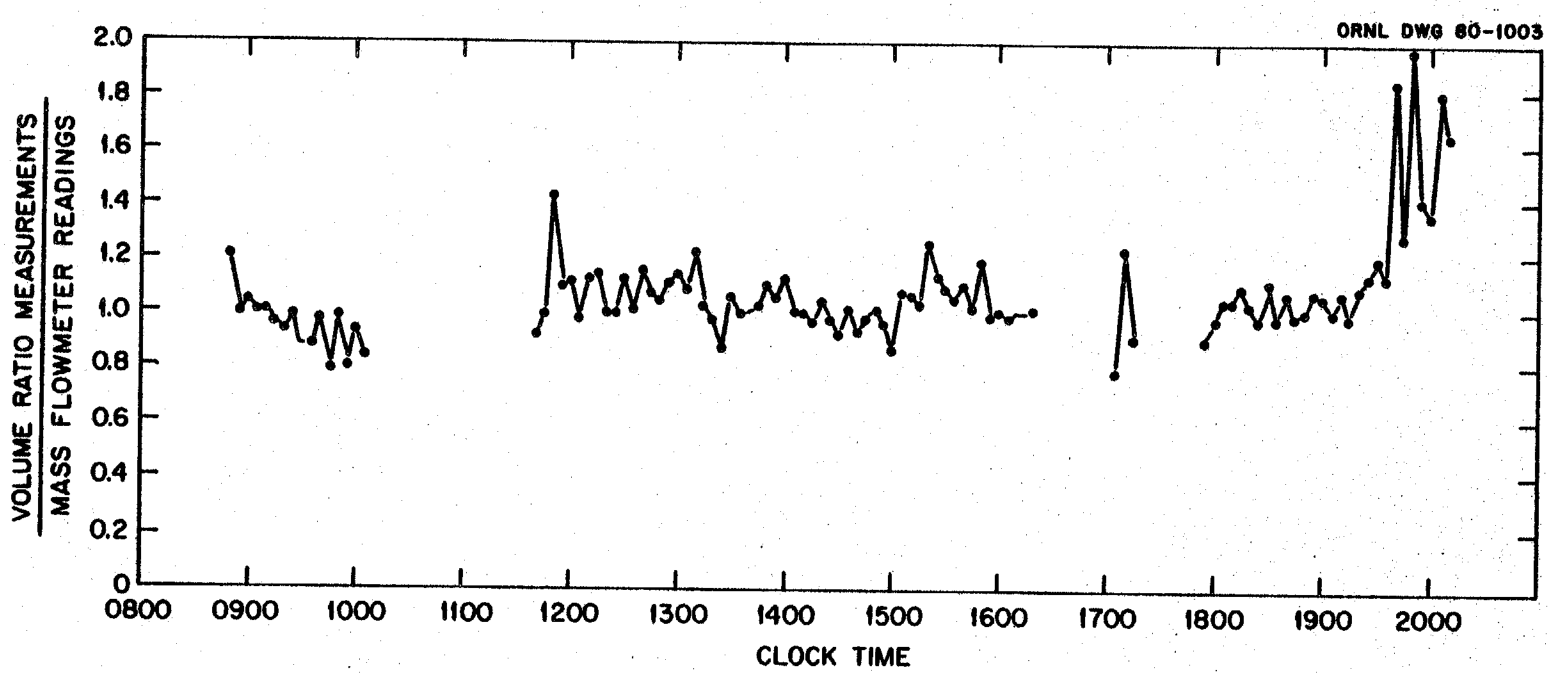

Fig. 30. Comparison of mix ratios as determined by mass-meter readings and volume ratio, Injection ILW-18.

At 1620, the flow of waste solution to the mixer jet became erratic and the injection was halted. A fragment of caked cement behind the jet, which was found to be the cause of the trouble, was removed, and the injection was restarted at 1746.

At 1945, an appreciable quantity of solids remained even though most of the waste solution had been injected. These solids were mixed with ∿12,000 ℓ (3,000 gal) of water that had been pumped into Tank T-4 and agitated to suspend some of the sludge that had settled in this tank during 15 years of use. At this time, the mix ratio was increased to between 1.08 and 1.2 kg/ℓ (9 and 10 lb/gal) so that more of the available solids would be used. Perhaps coincidentally, the mass-meter readings dropped sharply (indicating an improbably low mix ratio). The volume ratio calculations were used for mix ratio determination during the remainder of the injection.

Flow was switched to water at 2010, and the solids flow was shut off at 2014. The wiper plug was pumped down the well with 5700 ℓ (1500 gal) of water, and the casing was flushed with 7600 ℓ (2000 gal) of water. The well was then valved shut and the equipment washed. The piping connections to the wellhead were disconnected, and bull plugs were used to seal the wellhead shut-off valves. This precaution was necessary because some leakage back up the injection well had apparently occurred after the last two injections despite a closed shutoff valve.

The pressures in the rock cover wells were read at intervals during the injection. The results are given in Table 20. The largest pressure changes were observed in wells NE-125, NE-200, and S-200.

6.3 Data Analysis

The volume of waste solution or pit water pumped during this injection was measured by three methods. The solution flow to the mixer was measured by a Halliburton turbine flowmeter as well as a recording orifice meter. The volume of waste solution pumped was measured by the change in the level of the tank solution. The agreement between the tank level measurements and the turbine flowmeter readings was generally

Table 20. Pressure readings for rock cover wells, in kPa (psig) — Injection ILW-18

Rock cover well	Pre-Injection	Readings taken on May 19, 1979, at:						
		0920	1200	1310	1430	1545	1825	1930
E-300	3.4 (0.5)	3.4 (0.5)	14 (2)	14 (2)	14 (2)	10.3 (1.5)	7 (10)	14 (2)
NE-125	-3.4 (-0.5)	3.4 (0.5)	172 (25)	314 (45.5)	297 (43)	255 (37)	[a]	[a]
NE-200	-25.5 (-3.7)	-25.5 (-3.7)	38 (5.5)	145 (21)	269 (39)	276 (40)	303 (44)	390 (56.5)
N-200	0	0	0	34 (0.5)	0	0	0	0
N-275	0	0	3.4 (0.5)	-2 (-0.3)	0	0	17.2 (2.5)	24 (3.5)
NW-175	0	-3.4 (-0.5)	3.4 (0.5)	-2 (-0.3)	-10.3 (-1.5)	-14 (-2)	-17.2 (-2.5)	-21 (-3)
NW-250	0	0	0	0	0	0	0	0
W-300	0	0	0	0	0	0	0	0
S-200	162 (23.5)	200 (29)	260 (37.5)	255 (37)	241 (35)	234 (34)	207 (30)	186 (27)

[a]Off scale.

very good; the orifice meter readings ranged from 2% higher to 30% lower than the tank level measurements. It was noted that the turbine flowmeter readings were 10% low while tank T-9 was being emptied. During Injections ILW-15 and ILW-17, errors of the same size were noted for tank T-9. (Tank T-9 was not used during ILW-16.) This correspondence of errors suggested that the calibration tables for this tank should be checked against the dimensions given in the tank drawings. This check indicated that the calibration tables are ∿10% in error. Because the turbine meter readings are generally more convenient to use than the tank level readings, they are used in the subsequent calculations.

The volume of injected grout was measured by the stroke counter on the injection pump. These volumes were noted at 5-min intervals.

Weights (strain gages) of bins 3 and 4 were noted at intervals. No measurements are available for bins 1 and 2 since bin 2 has no usable weigh gage installed and the strain gage on bin 1 did not function during this injection. The bin level measurements (plumb bobs) were not used in this injection because of a fear that the float part of the unit might be broken from the unit, as had occurred in an earlier injection.

The strain gage on bin 3 did not give credible readings; both the zero and the slope of the curve were badly in error. The strain gage on bin 4 gave values that agreed reasonably well with the mix ratio calculations.

The bulk storage bins contained an appreciable amount of solids at the end of the injection. Fifteen truck loads of solids were removed from the four storage bins and the P-tanks. Seven loads were removed from bin 2, and two loads were removed from each of the other bins. The cone of bin 2 was essentially full, while 1 m (3 to 4 ft) of solids remained in the other tanks. Each truck load is estimated to contain ∿1000 kg (2200 lb) of solids; the total weight of solids remaining after the injection is therefore estimated to be 15,000 kg (33,000 lb). The net consumption of solids was therefore 283,000 kg (620,000 lb).

Mix ratios are calculated during an injection from the mass-meter readings and from the volume ratio calculations. After an injection, an actual mix ratio can be determined for each storage bin, based on the weight of solids actually consumed. Table 21 is a comparison of these mix ratios. The results from the mass-meter and the volume ratio calculations are generally similar (as would be expected from the comparison shown in Fig. 30). The major difference is in the P-tank values and is a reflection of the improbably low mass-meter readings during the last 30 min of the injection. The actual mix ratio is appreciably less than either value measured during the injection for bin 2, but nearly the same during the rest of the injection.

The recorded mass flow rate of solids was ∿12% lower than the values of the mass-meter readout that were noted at intervals. The recorded mix ratio was ∿25% lower than the ratio calculated from the mass-meter and turbine flowmeter readouts.

6.4 Evaluation of the Injection

This injection, like ILW-17, was characterized by the smoothness of operation. The solids flowed evenly from the bulk storage bins, and the control of the solids to liquid mixing was generally good.

It becomes more apparent with each injection that the facility is nearing the end of its useful life. Several malfunctions (that could be attributed to worn equipment) occurred despite the pre-injection maintenance. Extensive reconditioning would be required if further use of the facility were planned.

A good measurement of the mix ratio was provided by both the mass-meter and the volume ratio calculations. The value of having both measurements is demonstrated by the divergence in readings that occurred during the last 30 min of the injection. During this time, the cross-check provided by the independent mix ratio determinations allowed us to recognize the problem, realize the probable cause, and complete the injection with the mix ratio measured and controlled by volume ratio calculations.

Throughout the injection, the grout appeared fluid and without excessive viscosity, despite the fact that mix ratios frequently averaged 0.84 to 0.96 kg/ℓ (7 to 8 lb/gal) and sometimes were ≥1.2 kg/ℓ (10 lb/gal). Tests performed prior to the injection had indicated that material with

Table 21. Comparison of mix ratios for Injection ILW-18

	Bin				
	2	3	1	4	P-tanks
Waste volume, ℓ (gal)	81,340 (21,490)	67,000 (17,700)	66,600 (17,600)	81,800 (21,600)	50,300 (13,300)
Solids consumed					
Tank weight, kg (lb)	57,300 (126,000)	57,300 (126,000)	59,100 (130,000)	58,200 (128,000)	50,900 (112,000)
Mass meter, kg (lb)	68,080 (149,770)	57,400 (126,200)	57,400 (126,200)	61,500 (135,200)	44,000 (96,800)
Volume ratio, kg (lb)	67,100 (147,560)	62,950 (138,500)	58,780 (129,300)	57,400 (126,200)	53,550 (117,800)
Mix ratio					
Tank weight, kg/ℓ (lb/gal)	0.70 (5.86)	0.85 (7.11)	0.89 (7.37)	0.71 (5.93)	1.01 (8.42)
Mass meter, kg/ℓ (lb/gal)	0.84 (6.97)	0.86 (7.12)	0.86 (7.15)	0.75 (6.26)	0.87 (7.28)
Volume ratio, kg/ℓ (lb/gal)	0.83 (6.87)	0.94 (7.82)	0.88 (7.32)	0.70 (5.84)	1.06 (8.86)

mix ratios in excess of 0.72 kg/ℓ (6 lb/gal) would be quite thick and difficult to pump. The reason for this discrepancy between laboratory tests and field results is not known. It may be caused by the additional aeration that is given to the mix in the field during the injection. An extra transfer during blending is known to have a marked effect on mix properties, and it is not unreasonable to believe that additional aeration would have a similar effect. This phenomenon needs investigation.

6.5 Post-Injection Operations

All cased observation wells that were serviceable were logged following the injection. Well NE-125, whose casing was pulled apart during Injection ILW-13, is badly contaminated and no longer usable. The casing of well W-300 was ruptured during Injection ILW-14. No grout sheet that could be attributed to Injection ILW-18 was noted in well E-300, N-150, or NW-100. A new peak was observed in well S-220 at 233 m (765 ft); a small peak was observed in well N-100 at 226 m (742 ft).

Bleedback of water from the injection well was started on January 21. The initial bleedback rate was 2 ℓ/min; this rate dropped to a sporadic trickle after 24 h. Between 1500 and 1900 ℓ (400 to 500 gal) was collected during this time.

7. EVALUATION OF THE INJECTION SERIES

7.1 Summary of Injection Parameters

Tables 22 and 23 give inspection parameters in metric units and in English equivalents, respectively, for each injection in this series. Values for previous operational injections are also included in these tables. Values for the early experimental injections have been previously published.[3]

7.2 Grout Sheet Monitoring

The results obtained from the logging of the cased observation wells are presented in Sects. 3.7, 4.5, 5.5, and 6.5. These results, corrected for the well surface elevations and deviations from the vertical, are given in Table 24. A schematic representation is shown in Fig. 31. The pattern of the grout sheets is similar to that indicated by previous injections — grout sheets that generally follow the bedding planes (i.e., slope about 15° to the north) but occasionally cross over other grout sheets and go down-dip. Multiple grout sheets from the same injection are observed.

One of the observation wells (NE-125) was lost during this injection series (after Injection ILW-16) when the cap was broken during cold weather and a small amount of contaminated water leaked up the well, leaving it too contaminated to log. Five usable wells remain in service — N-100, N-150, NW-100, S-220, and E-320. Three of them are in the same quadrant, and one (E-320) has never been intersected by any grout sheet. The information that can be obtained from logging the observation well network is therefore quite limited, and additional wells would be needed if injections at this site were continued.

The readings of the pressure changes in the rock cover monitoring wells during the four injections suggest patterns for the grout sheets that are not inconsistent with the logging results. An increase in rock cover well pressure during an injection is assumed to indicate a grout sheet passing beneath the base of the well, while a fall in pressure is

Table 22. Summary of injection parameters — metric units

Injection number	Date	Depth (m)	Waste volume (ℓ)	Waste-plus-water volume (ℓ)	Grout volume (ℓ)	Mix ratio (kg solid / ℓ liquid)	^{90}Sr (Ci)	^{137}Cs (Ci)	^{244}Cm (Ci)	^{239}Pu (Ci)
Experimental injections										
1–7	Feb. 1964–Aug. 1965	288–266		1,731,000	2,566,000		1,436	5,237		
Operational injections										
ILW1A	Dec. 12, 1966	266	136,260	264,700	360,300					
ILW1B	Dec. 13, 1966	266	94,410			0.74	3	19,950	NA	NA
ILW2A	Apr. 20, 1967	263	325,500	623,800	872,100					
ILW2B	Apr. 24, 1967	263	234,700			0.73	1,050	58,500	NA	NA
ILW3A	Nov. 28, 1967	263	117,300	374,900	555,500					
ILW3B	Nov. 29, 1967	263				0.66	9,000	17,000	NA	NA
Water test	Dec. 13, 1967	260		169,200						
ILW4A	Apr. 3, 1968	260	90,900							
ILW4B	Apr. 4, 1968	260	235,400	367,500	494,600	0.61	4,300	51,900	NA	1.10
ILW5	Oct. 30, 1968	257	309,600	329,700	435,900	0.67	500	69,400	NA	1.15
ILW6	June 11, 1969	257	300,300	347,300	478,200	0.65	8,900	89,000	NA	0.24
ILW7	Sept. 23, 1970	257	314,200	407,500	551,400	0.66	2,747	44,833	19.2	1.77
ILW8	Sept. 29, 1972	254	275,200	308,100	411,100	0.88	45	28,000	0.20	0.13
ILW9	Oct. 17, 1972	254	258,500	286,100	431,500	0.94	231	23,400	6.51	None
ILW10	Nov. 8, 1972	254	320,800	354,200	503,300	0.85	1,330	18,800	26.67	0.37
ILW11	Dec. 5, 1972	254	286,800	310,800	475,000	0.86	1,100	23,500	155.74	None
ILW12	Jan. 24, 1975	251	97,300	113,900	159,300	0.79	1,324	12,752	1.02	None
ILW13	Apr. 29, 1975	251	306,600	325,100	477,300	0.76	3,368	35,750	17.83	0.03
ILW14	June 20, 1975	251	314,000	350,000	525,000	0.80	2,874	30,592	3.58	None
ILW15	June 30, 1977	251	344,400	393,600	549,000	0.66	138	26,390	None	0.66
ILW16	Nov. 17, 1977	248	208,900	224,100	300,900	0.86	1,618	14,964	None	None
ILW17	Sept. 1, 1978	244	311,500	338,800	520,400	0.80	90	22,270	2.27	0.07
ILW18	May 18, 1979	241	314,200	368,800	526,100	0.77	28	16,880	0.19	0.29
Total ILW			5,397,600	6,258,000	8,796,000		38,640	603,881		

Table 23. Summary of injection parameters — English units

Injection number	Date	Depth (ft)	Waste volume (gal)	Waste-plus-water volume (gal)	Grout volume (gal)	Mix ratio $\left(\frac{\text{lb solid}}{\text{gal liquid}}\right)$	^{90}Sr (Ci)	^{137}Cs (Ci)	^{244}Cm (Ci)	^{239}Pu (Ci)
<u>Experimental injections</u>										
1-7	Feb. 1964– Aug. 1965	845– 872		457,300	678,000		1,436	5,237		
<u>Operational injections</u>										
ILWIA	Dec. 12, 1966	872	36,000	69,931	95,197	6.2	3	19,950	NA[a]	NA
ILW1B	Dec. 13, 1966	872	26,000							
ILW2A	Apr. 20, 1967	862	86,000	164,800	230,405	6.1	1,050	58,500	NA	NA
ILW2B	Apr. 24, 1967	862	62,000							
ILW3A	Nov. 28, 1967	862	31,000	99,050	146,751	5.5	9,000	17,000	NA	NA
ILW3B	Nov. 29, 1967	862	52,000							
<u>Water test</u>	Dec. 13, 1967	852		44,709	44,709					
ILW4A	Apr. 3, 1968	852	24,010	97,090	130,675	5.1	4,300	51,900	NA	1.10
ILW4B	Apr. 4, 1968	852	62,180							
ILW5	Oct. 30, 1968	842	81,800	87,110	115,174	5.6	500	69,400	NA	1.15
ILW6	June 11, 1969	842	79,350	91,750	126,331	5.4	8,900	89,000	NA	0.24
ILW7	Sept. 23, 1970	842	83,000	107,650	145,670	5.5	2,747	44,833	19.2	1.77
ILW8	Sept. 29, 1972	832	72,700	81,400	108,605	7.3	45	28,000	0.20	0.13
ILW9	Oct. 17, 1972	832	68,300	75,600	114,000	7.8	231	23,400	6.51	None
ILW10	Nov. 8, 1972	832	84,760	93,570	132,960	7.1	1,330	18,800	26.67	0.37
ILW11	Dec. 5, 1972	832	75,760	82,110	125,490	7.2	1,100	23,500	155.74	None
ILW12	Jan. 24, 1975	822	25,710	30,100	42,100	6.6	1,324	12,752	1.02	None
ILW13	Apr. 29, 1975	822	81,000	85,900	126,100	6.3	3,368	35,750	17.83	0.03
ILW14	June 20, 1975	822	82,970	92,470	138,700	6.7	2,874	30,592	3.58	None
ILW15	June 30, 1977	822	91,000	104,000	145,037	5.5	138	26,390	None	0.66
ILW16	Nov. 17, 1977	812	55,200	59,200	79,500	7.2	1,618	14,964	None	None
ILW17	Sept. 1, 1978	802	82,300	89,500	137,500	6.7	90	22,270	2.27	0.07
ILW18	May 18, 1979	792	83,014	97,434	139,000	6.4	28	16,880	0.19	0.29
Total ILW			1,426,054	1,653,374	2,323,907		38,640	603,881		

[a]NA = not analyzed.

Table 24. Elevations of grout sheets in observation wells

(All elevations are related to mean sea level)

Injection	Well	Grout sheet elevation (m)	Grout sheet elevation (ft)
ILW-15	Injection	-9.1	-30
	N-100	-1.5	-5
	N-150	-9.5	-31
	NE-125	-3.0	-10
		-4.6	-15
ILW-16	Injection	-6.7	-20
	N-100	9.8	32
	N-150	0.9	3
	NW-100	9.5	31
	S-220	-8.2	-27
ILW-17	Injection	-3.0	-10
	N-150	-12.5	-41
	S-220	-7.9	-26
ILW-18	Injection	S.L.	S.L.
	N-100	16.1	53
	S-220	-1.2	-4

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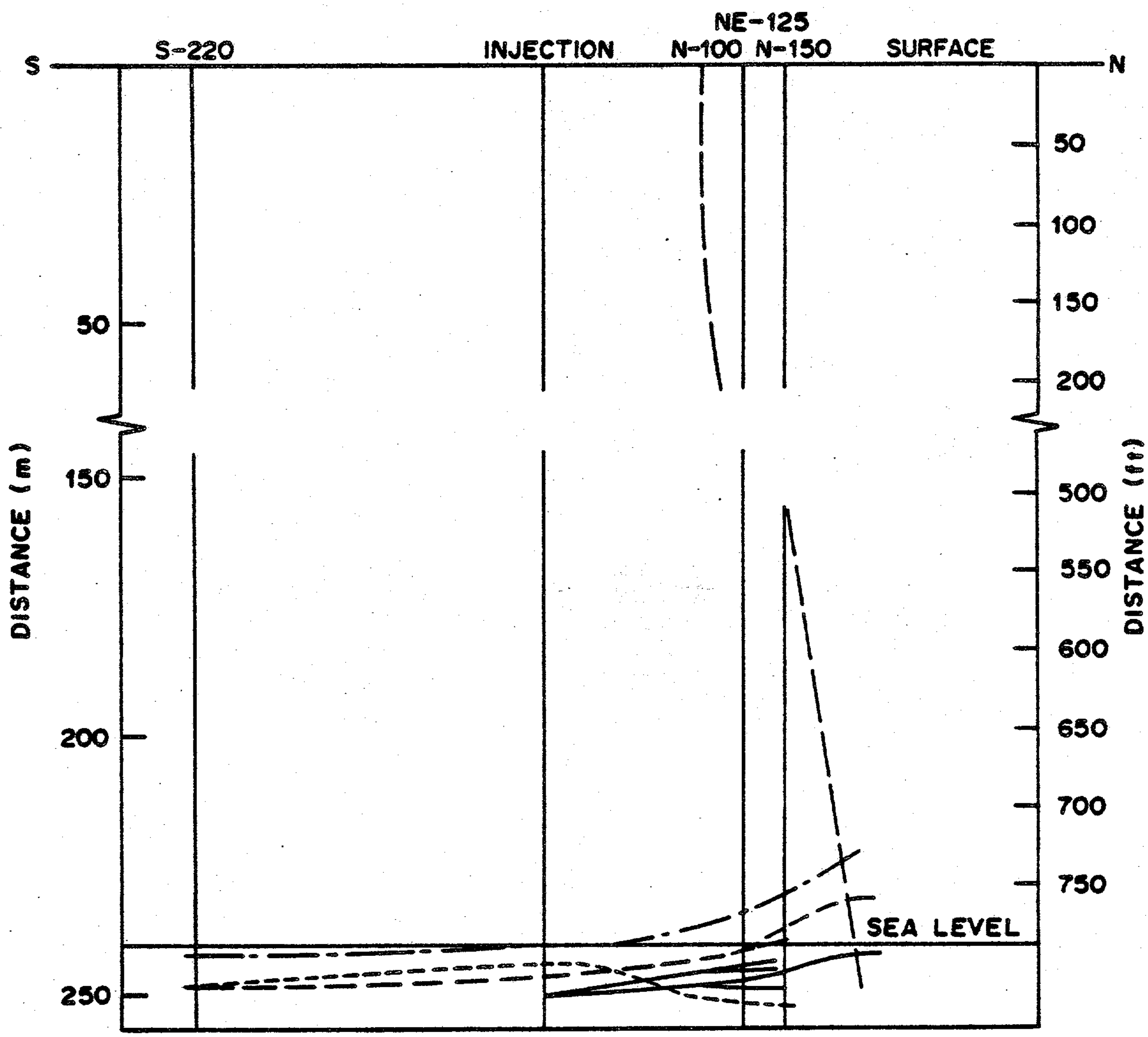

Fig. 31. Schematic representation of grout sheet monitoring results.

assumed to indicate a grout sheet passing nearby. Interpretation of the results is complicated, however, by two factors:

1. Deviation surveys were not always made prior to casing the wells. The amount of deviation is appreciable for some wells, but the direction cannot now be determined; the position at depth can only be approximated for these wells.

2. The magnitude of pressure response that is significant seems to vary widely from well to well; thus a record of the pressure response during numerous injections is needed to evaluate the results.

The well pressure readings during Injection ILW-15 indicate that the grout sheet went generally north; the logging results indicate the same orientation. The readings during Injection ILW-16 indicate that the grout sheet went north, northwest, and south; the logging results indicate the same orientation. The readings during Injection ILW-17 indicate that the grout sheet went east and southwest; the logging results indicate that the grout sheet went south but did not go northwest or southeast. The readings during Injection ILW-18 indicate that the grout sheet went south and northwest; the logging results indicate that the grout sheet went south with perhaps a finger to the northwest, but no major movement to the north. In general, these data suggest that the grout sheet movement during an injection can be determined from well pressure readings if (1) sufficient wells are available, (2) the well deviation is known, and (3) the sensitivity of the well to the grout sheet movements has been evaluated.

7.3 Field Behavior of Solids Mix

As early as Injection ILW-8 it was recognized that the properties of a grout made from a dry solids mix blended in the field differed appreciably from the properties of a grout made from a dry solids mix blended in the laboratory. The field-blended mix had a lower viscosity and a higher phase separation, even when the same ingredients were used in comparative blending tests. This phenomenon was compensated for by making all mix compatibility tests with field-blended samples, but the cause of the relative ineffectiveness of the field-blended mixes was not determined. In Injections ILW-15 through ILW-18, the number of transfers of solids during the blending operation was reduced by one in some cases; in each instance, the phase separation and the viscosity of the field-blended mix were much closer to the properties of the laboratory-blended mix. These results indicate that the solids transfer operation causes some deterioration in mix effectiveness (more mix is required for water retention), probably due to breakage of the attapulgite crystals. In Injection ILW-18, the entire solids inventory was transferred only twice (instead of three times, as had been traditional heretofore). The samples of this field-blended mix had properties quite similar to those of a laboratory-blended mix, and a lower-than-normal mix ratio was suggested for this injection. During the injection, the mix ratio was occasionally much higher than that recommended on the basis of the mix compatibility test data; yet the grout remained quite fluid with no suggestion of excessive viscosity. The dry solids mix that reached the mixing jet during the injection was apparently less effective than the dry solids mix that was sampled at the top of the bulk storage bins several days earlier. This deterioration in mix characteristics is probably caused by the aeration that occurs as the mix is withdrawn from the storage bin and passes through the air slide to the mixer. The magnitude of this deterioration, equivalent to at least 0.24 kg/ℓ (2 lb/gal), is appreciable. If not compensated for, it would result in the injection of a grout with an undesirably high phase separation. This is clearly undesirable; however, the mechanisms involved are not understood, and the magnitude of the compensation that is needed can only be estimated. More work on the loss in mix effectiveness is needed, particularly since the new shale fracturing facility will subject the mix components to even more aeration than does the existing facility.

7.4 Injection Operations

The most striking feature of this injection series was the significant improvement in the control of the mix ratio that occurred after a set of air pads had been installed on each of the bulk storage bins prior to Injection ILW-17. During the two injections in which these air pads were used, the flow of solids from the storage bins was much more uniform, the control of the solids flow was facilitated, and the mix ratio was maintained at a much more nearly constant value. It is very clear that a smooth, even flow of dry solids to the mixer is essential to the proper functioning of this facility.

The use of the volume ratio to determine the mix ratio has proved to be a valid operating technique. The mass flowmeter has been found to develop an occasional bias (caused by solids accumulating on the mixing cone), and the availability of an alternative technique for the measurement of the mix ratio provides a useful check on this instrument. In addition, the volume ratio measurements have proved to be an acceptable means of mix proportioning when the mass meter is completely inoperable.

Following two injections of this series, the injection well was found to be plugged with cement. Particular care was taken at the conclusion of Injection ILW-18 to seal off the well and prevent any backflow. (It was assumed that the problem was caused by a slow leakage back up the well after the well was shut in.) This careful isolation of the well appears to have solved the problem since the well was clear during the subsequent bleedback operation.

The facility is clearly approaching the end of its useful life. The number of usable observation wells is near a minimum, and several malfunctions that could be attributed to worn equipment occurred during the last several injections. Extensive reconditioning would be required if further use of the facility were planned.

A new hydrofracture facility, currently under construction, will utilize a new injection well and will have a new network of monitoring wells. Future operational injections will be made with this facility.

9. REFERENCES

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